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Title: r-Process nucleosynthesis and kilonovae in neutron star mergers

Author(s): Lippuner, Jonas

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r-Process nucleosynthesis and kilonovae in neutron star mergers

Jonas Lippuner

April 2, 2019

Astrophysics Seminar
University of Notre Dame
Notre Dame, IN

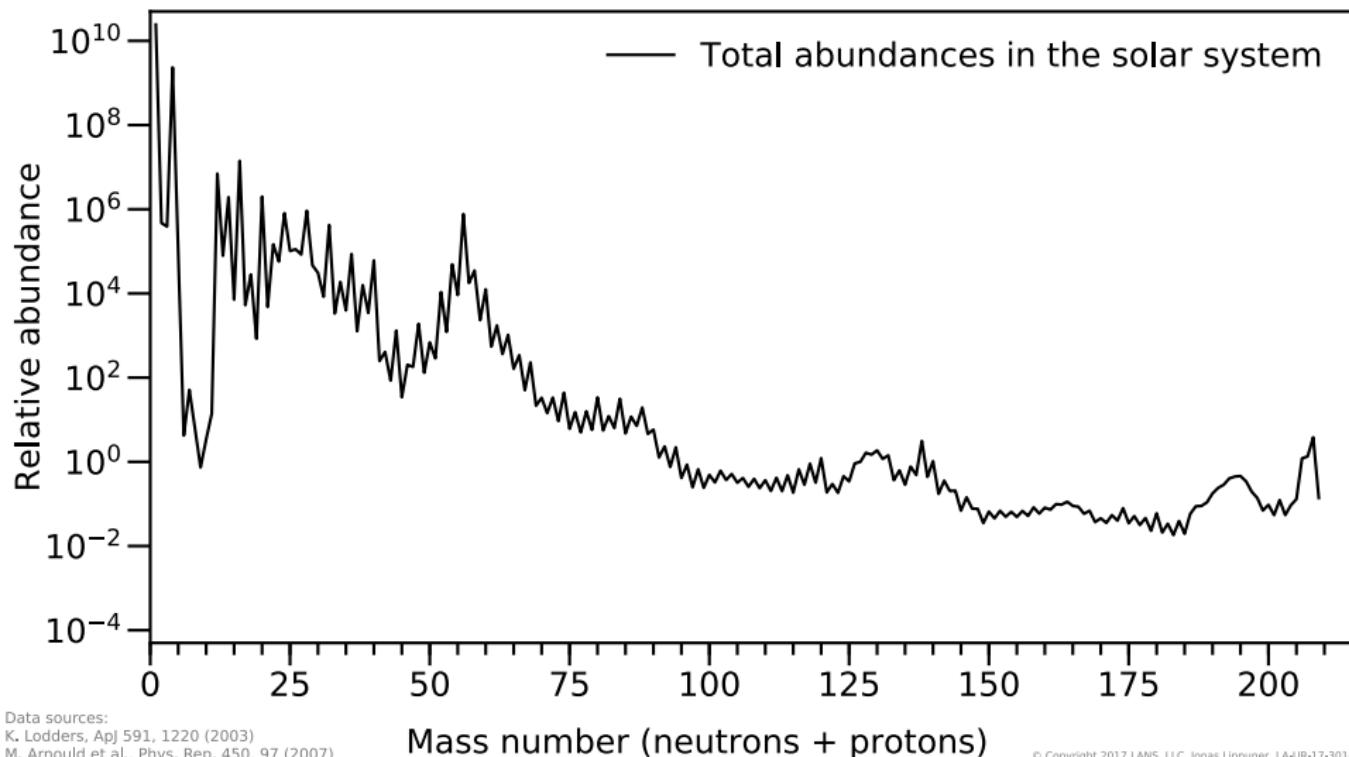


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Outline

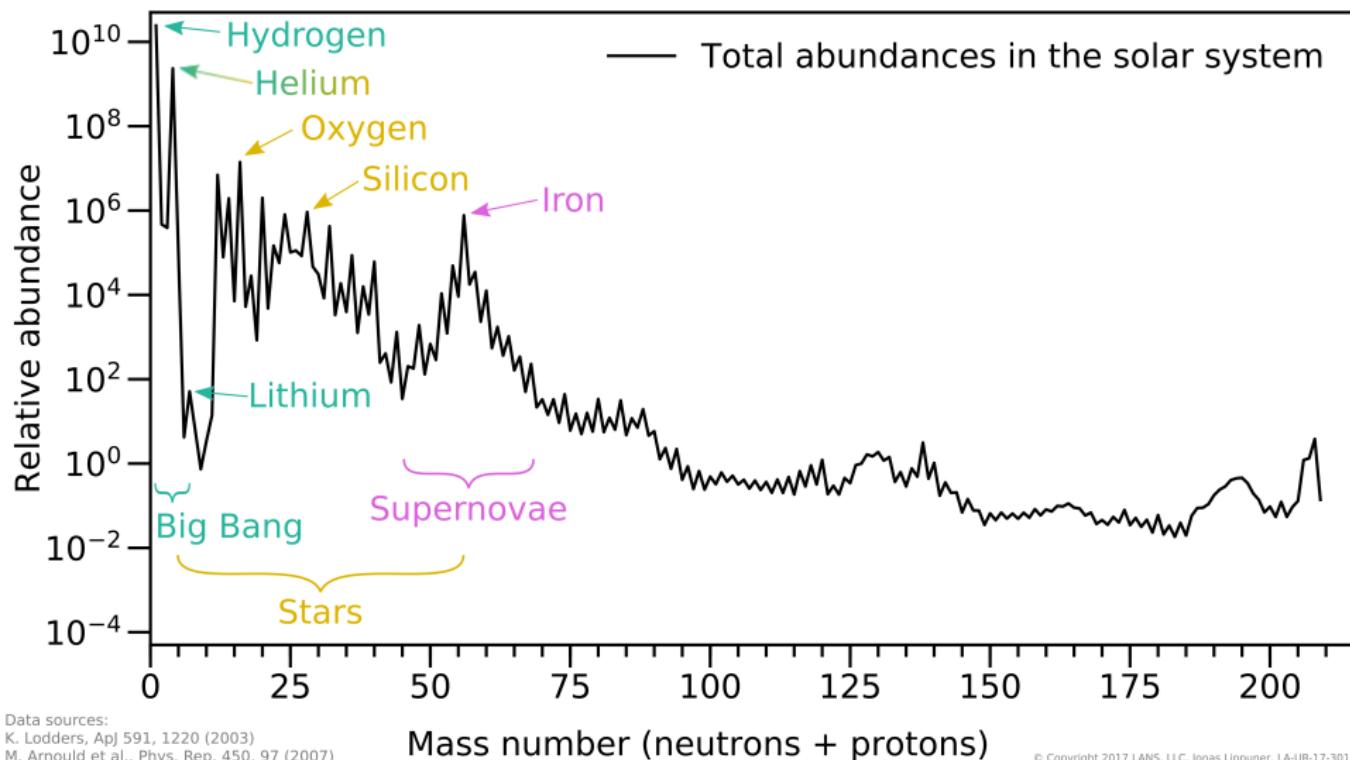
1. r-Process nucleosynthesis overview
2. r-Process in neutron star mergers
3. Observational signature and first detection

Solar system abundances



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Solar system abundances



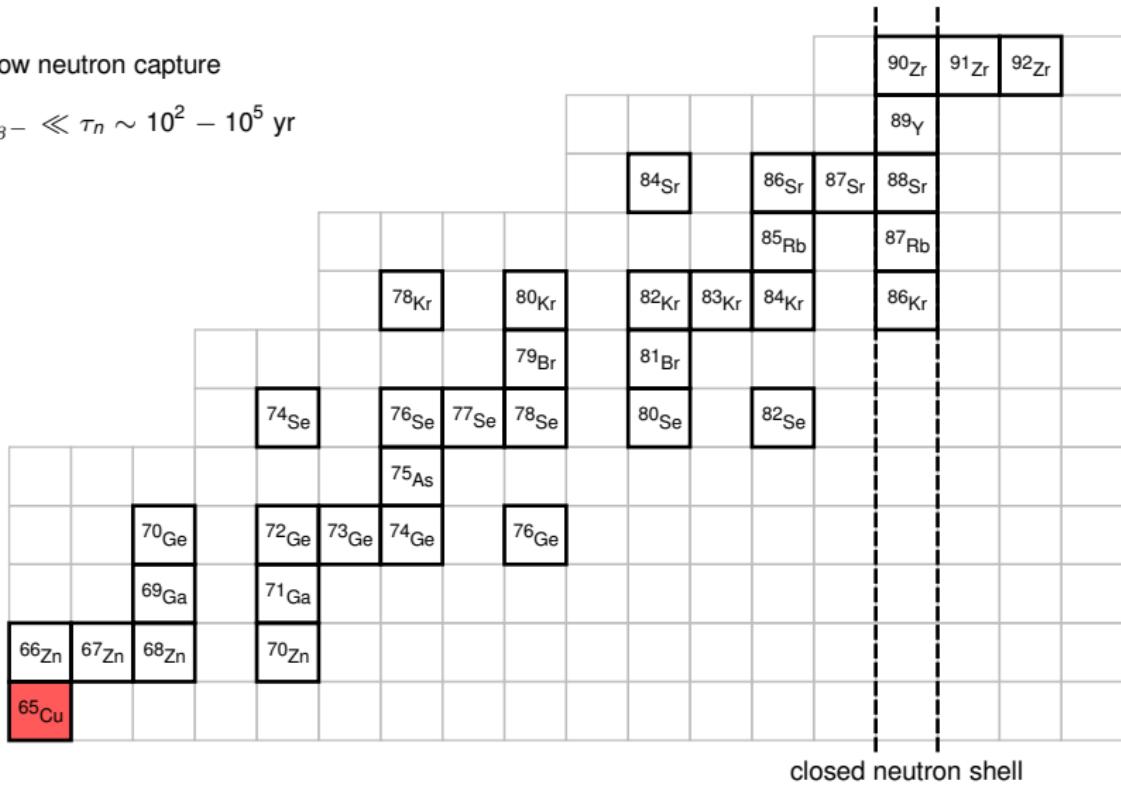
Data sources:
K. Lodders, ApJ 591, 1220 (2003)
M. Arnould et al., Phys. Rep. 450, 97 (2007)

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The s-process

slow neutron capture

$$\tau_{\beta^-} \ll \tau_n \sim 10^2 - 10^5 \text{ yr}$$

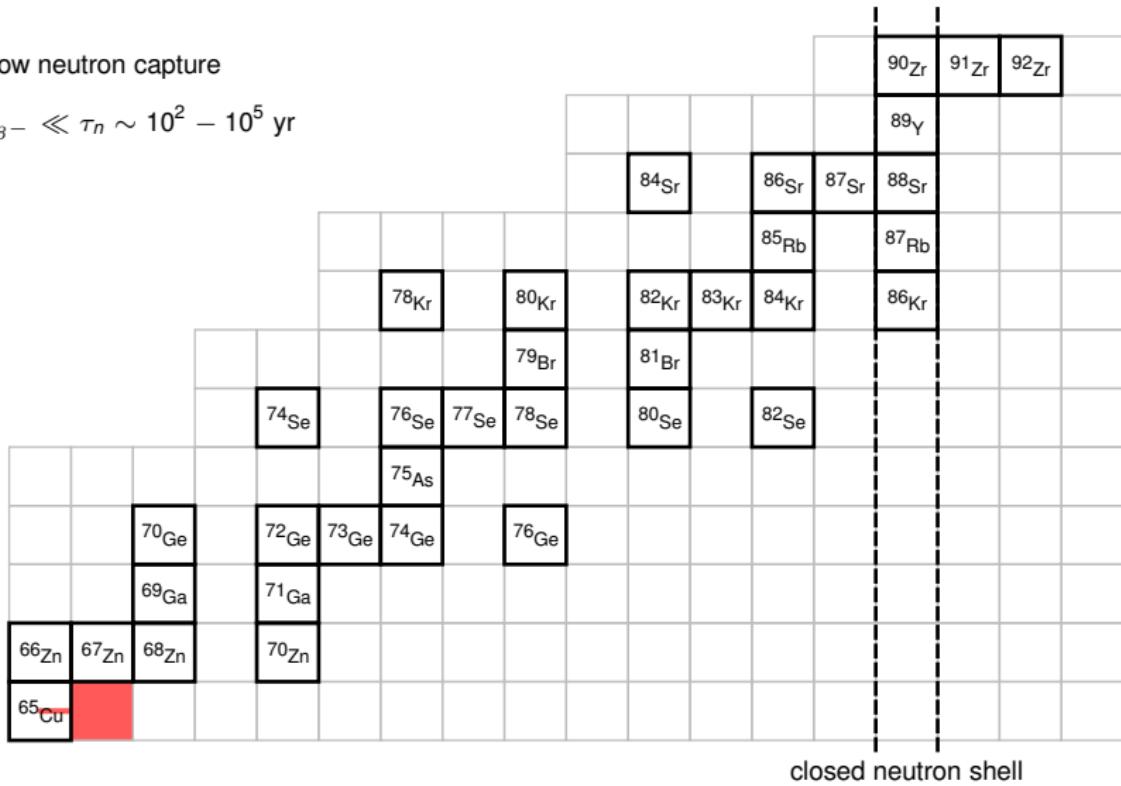


closed neutron shell

The s-process

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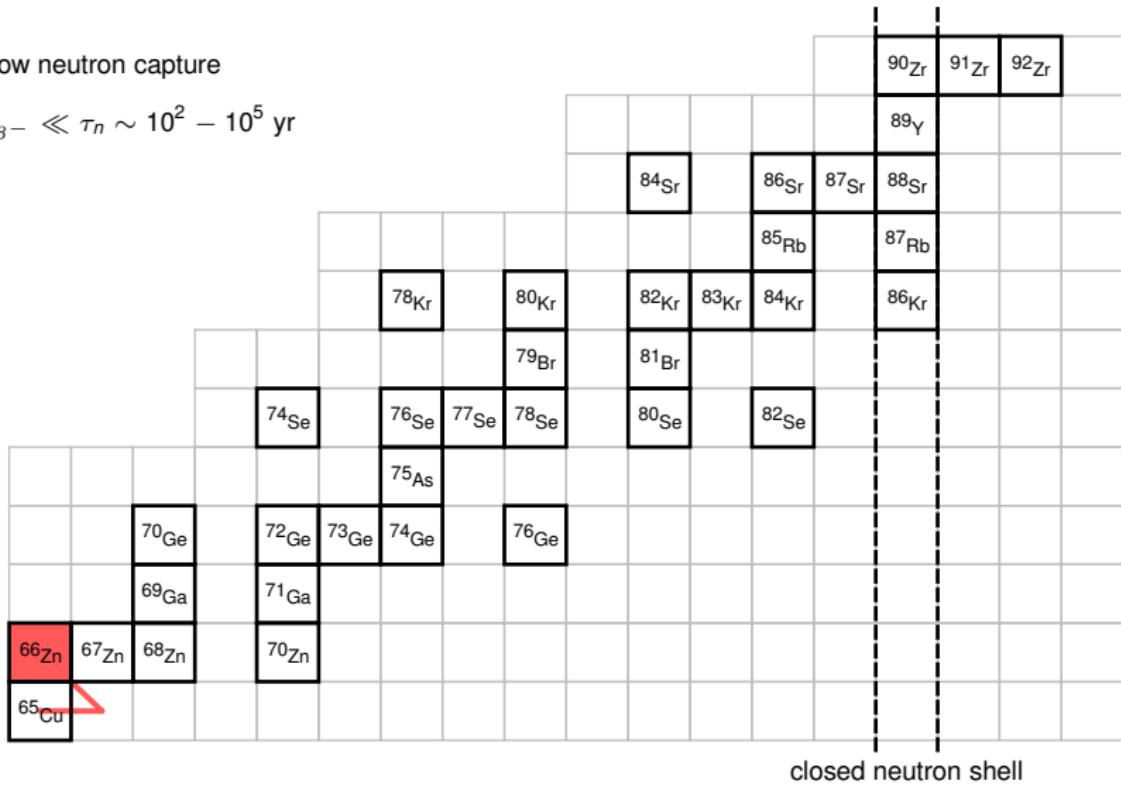
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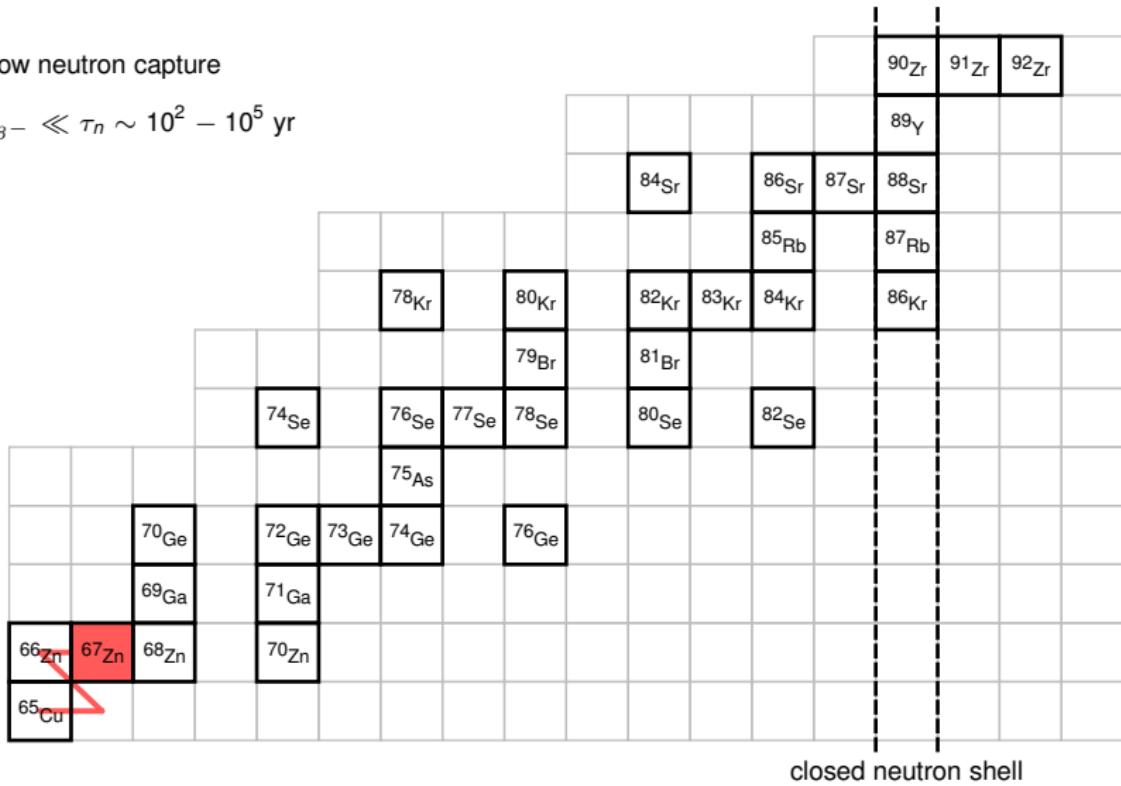
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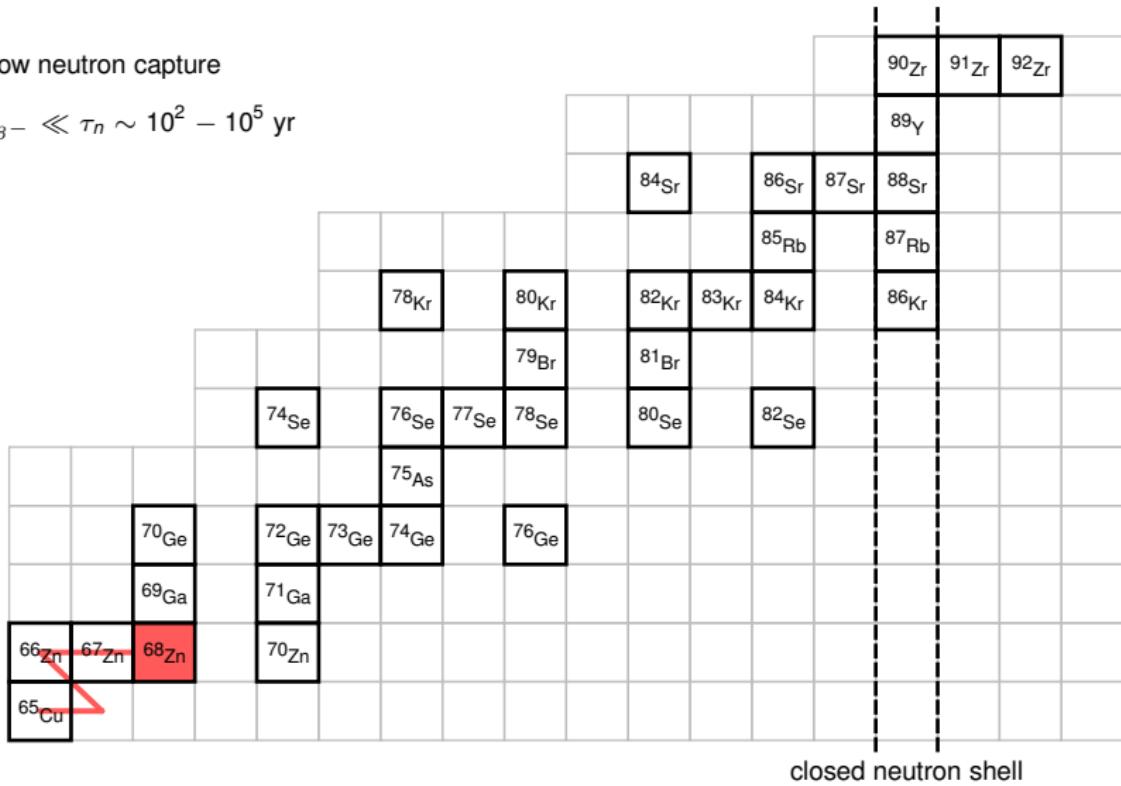
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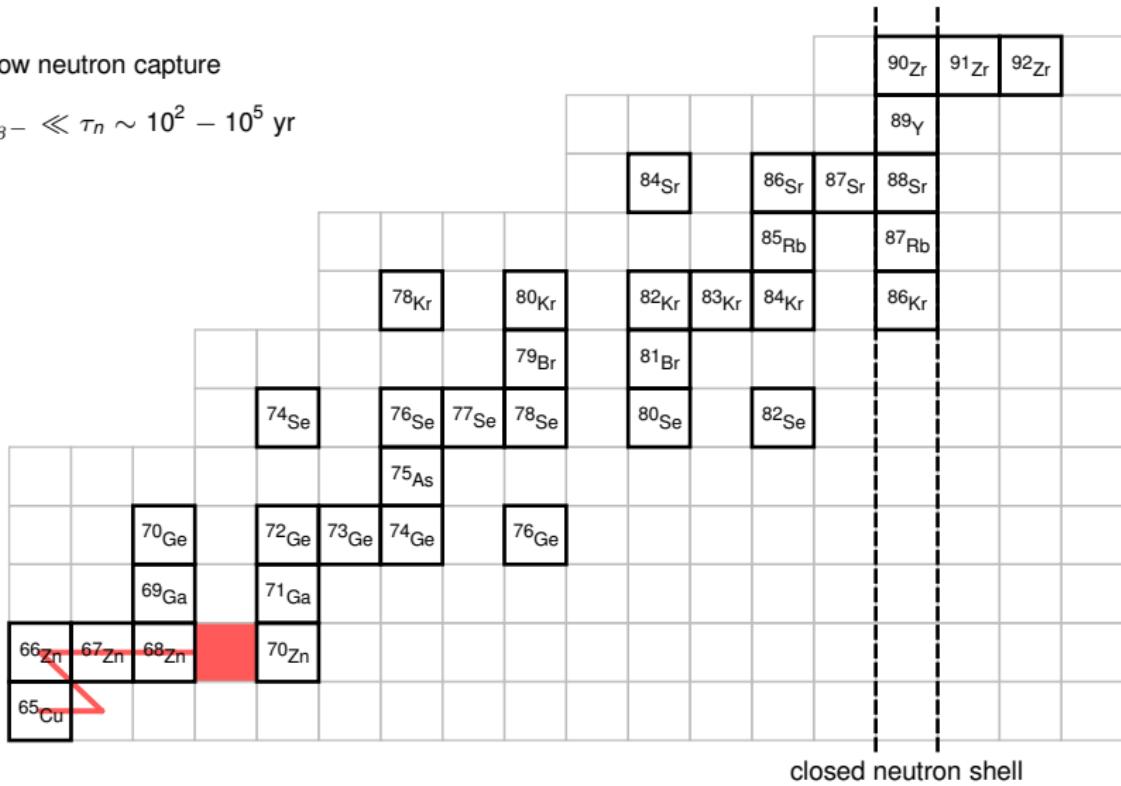
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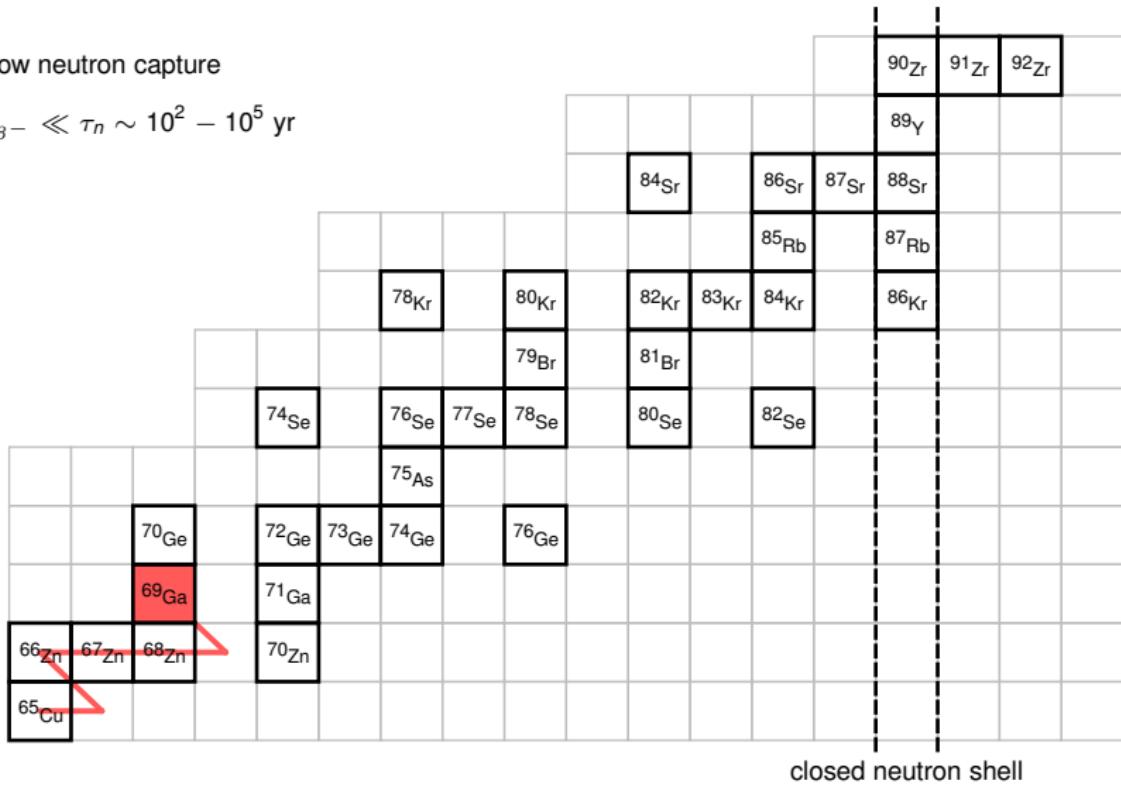


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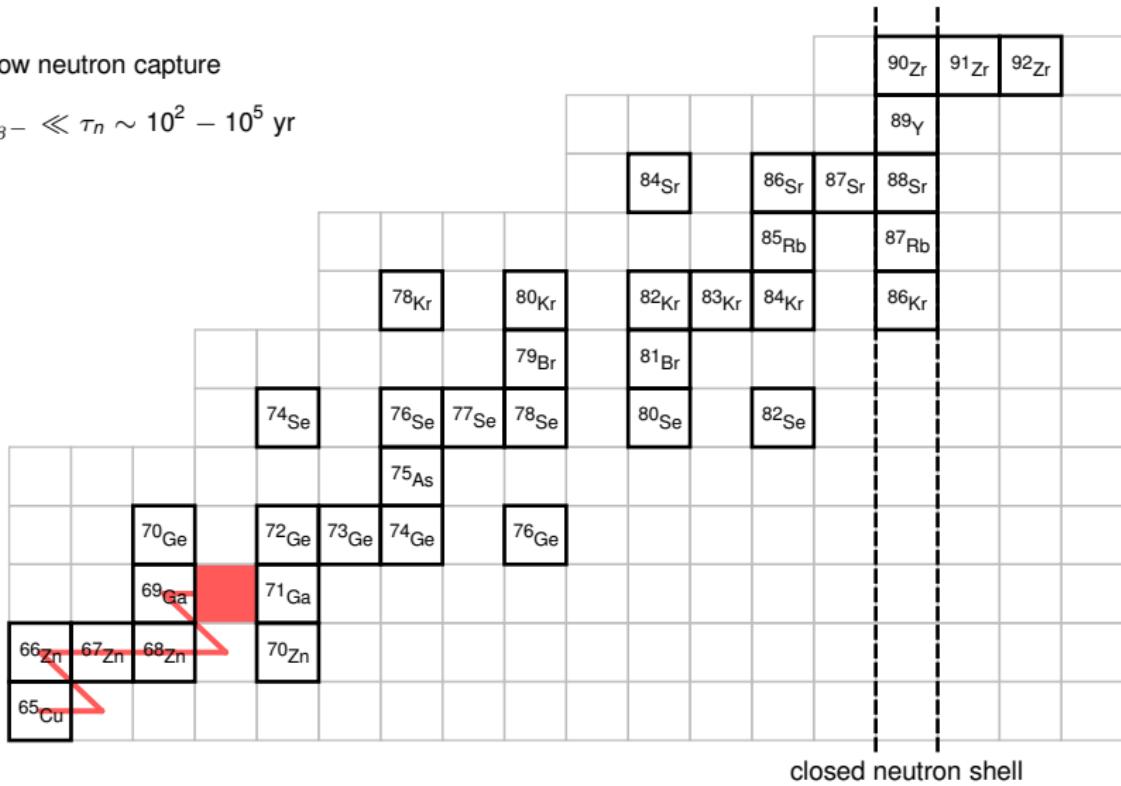
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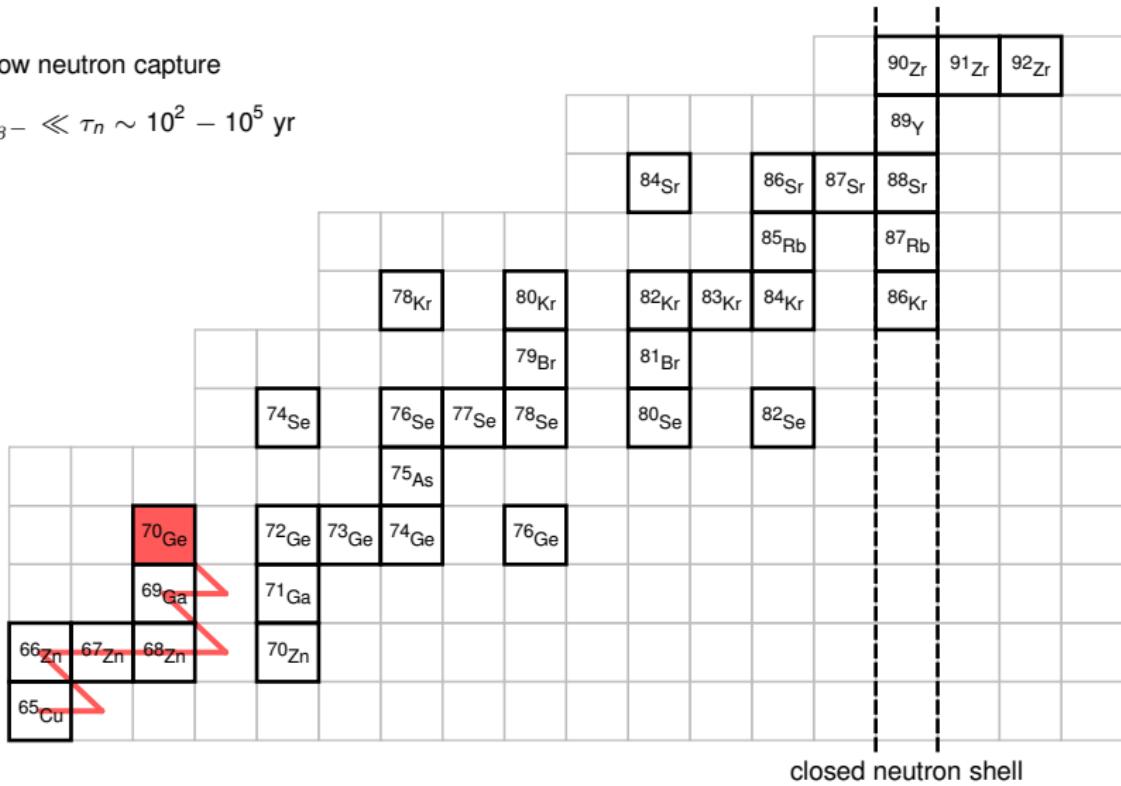
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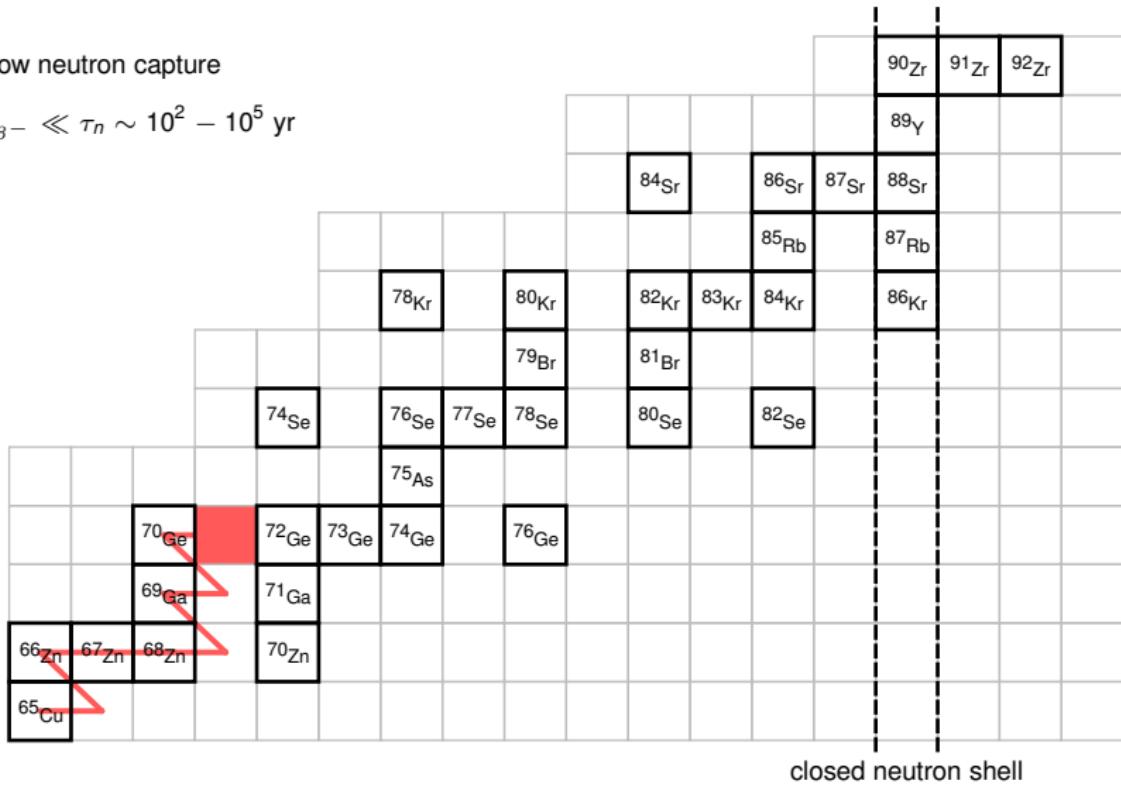


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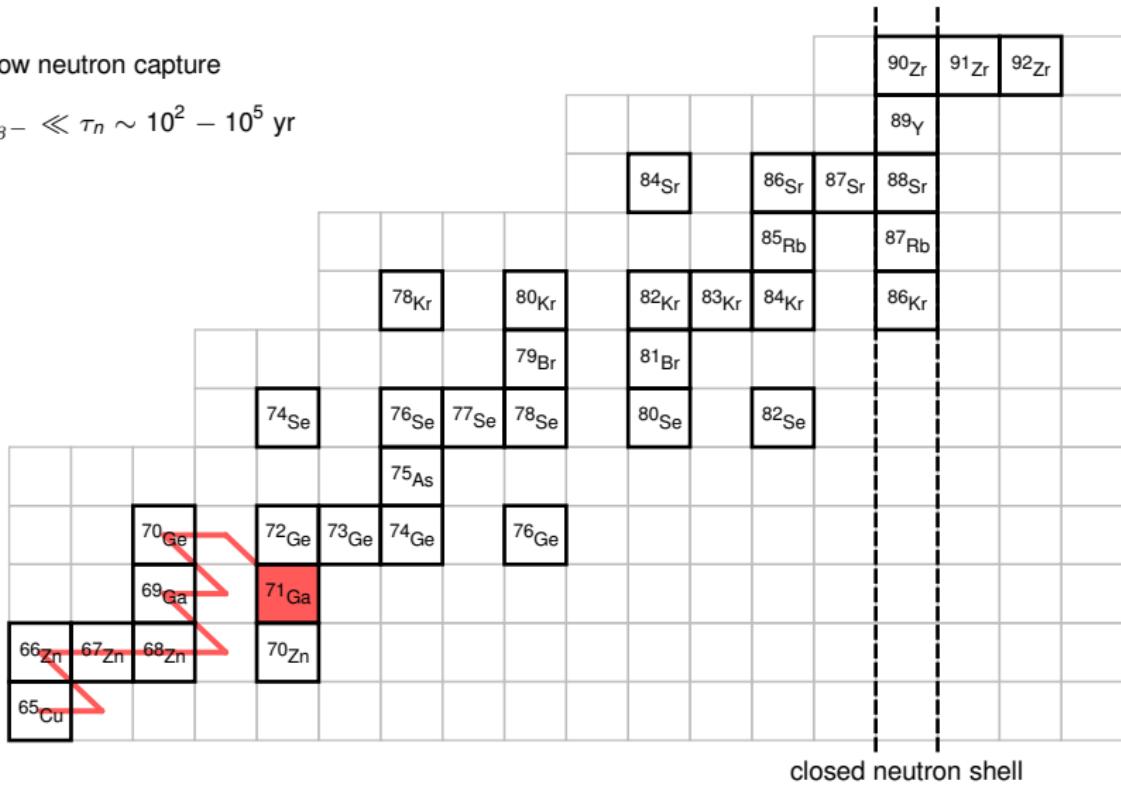


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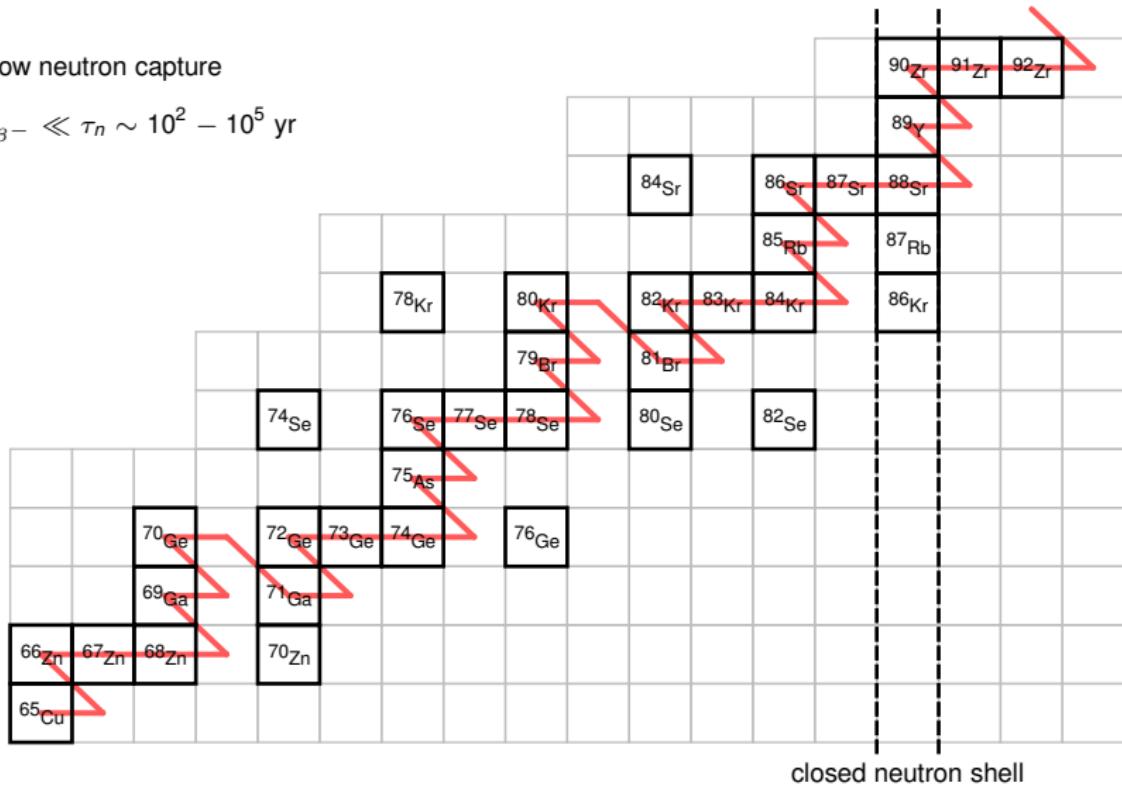


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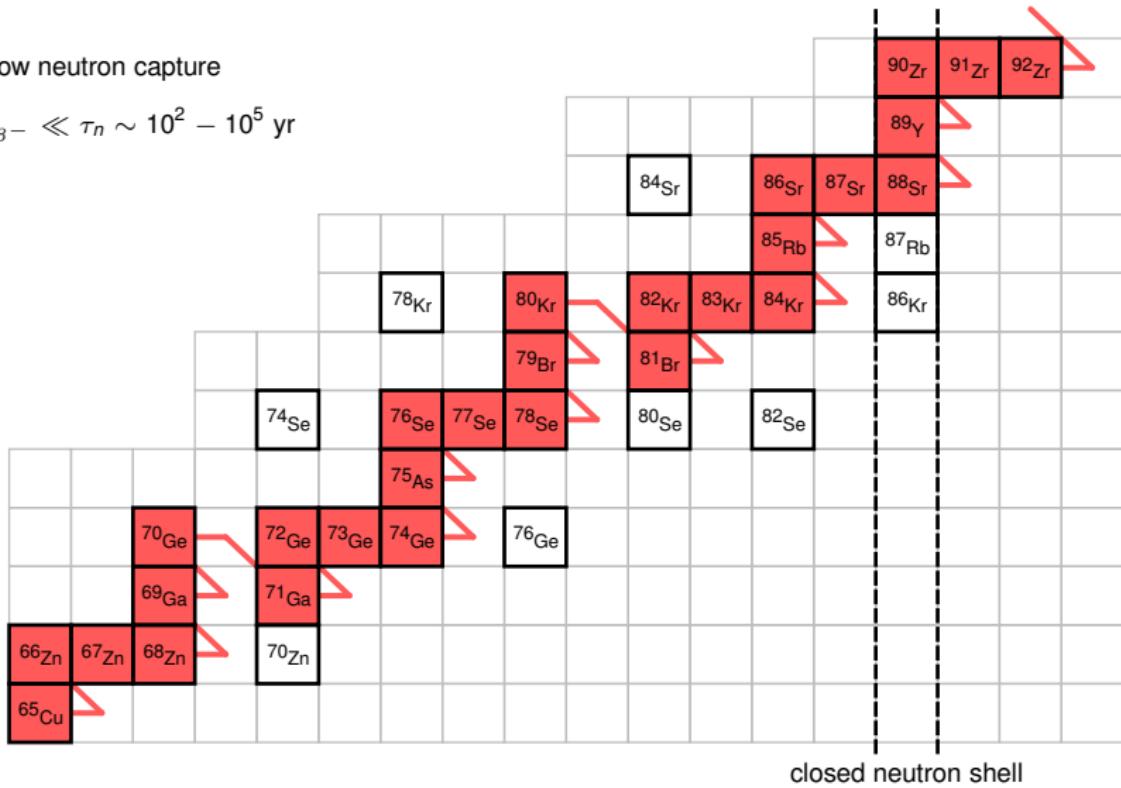


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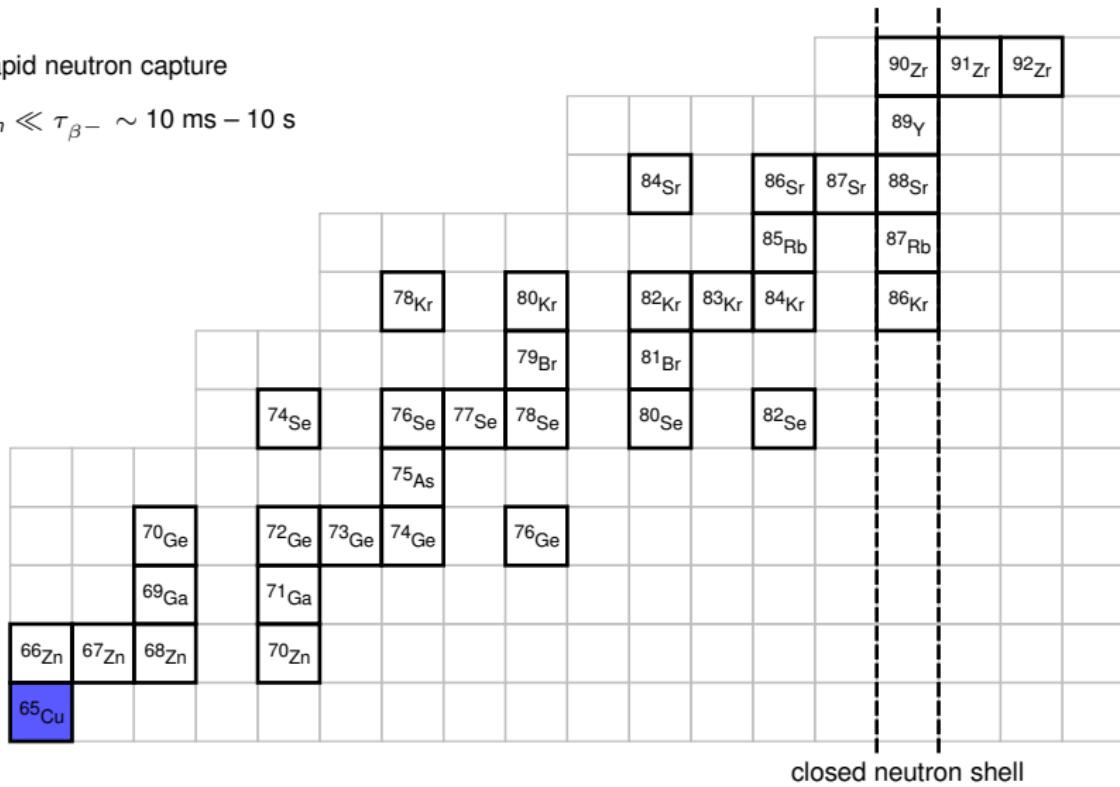


closed neutron shell

The r-process

rapid neutron capture

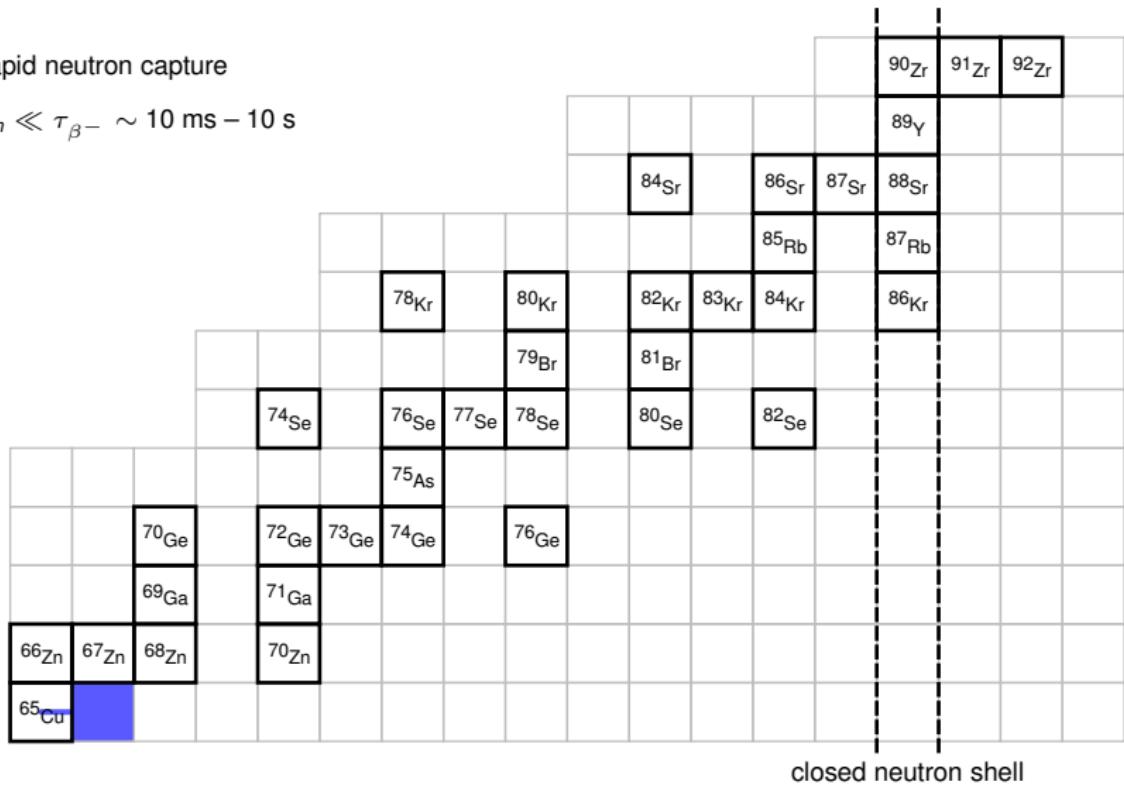
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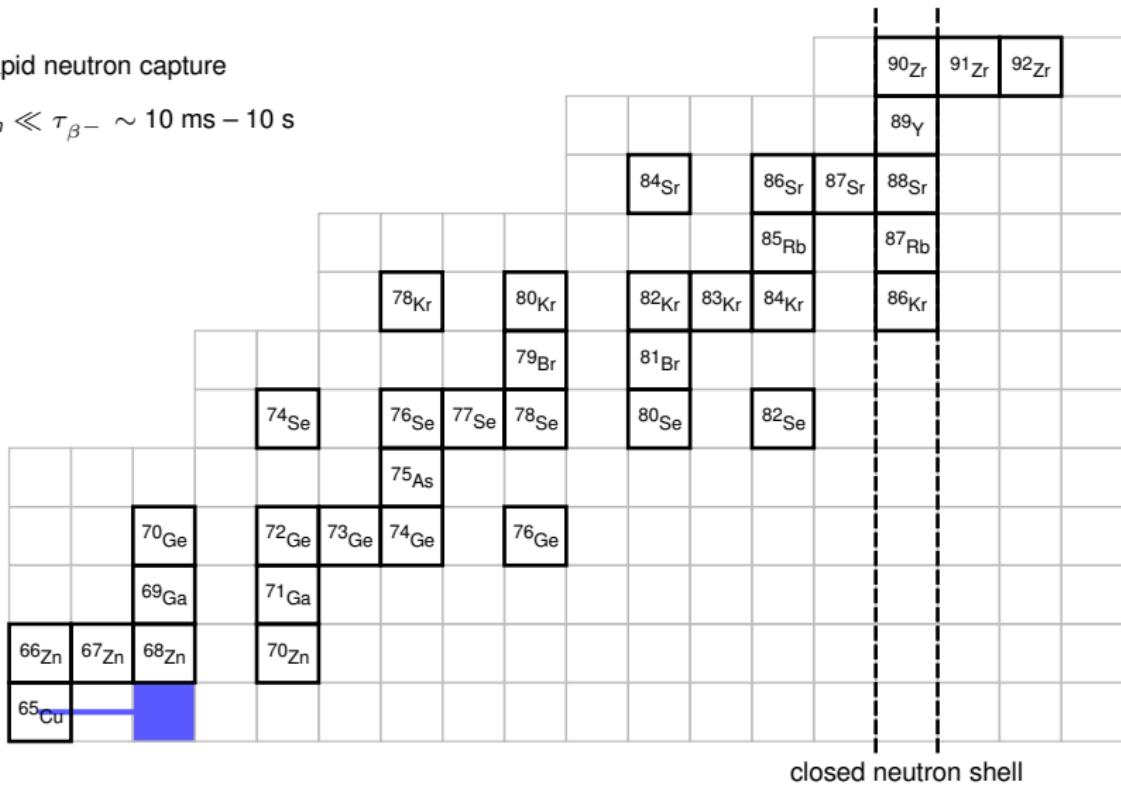


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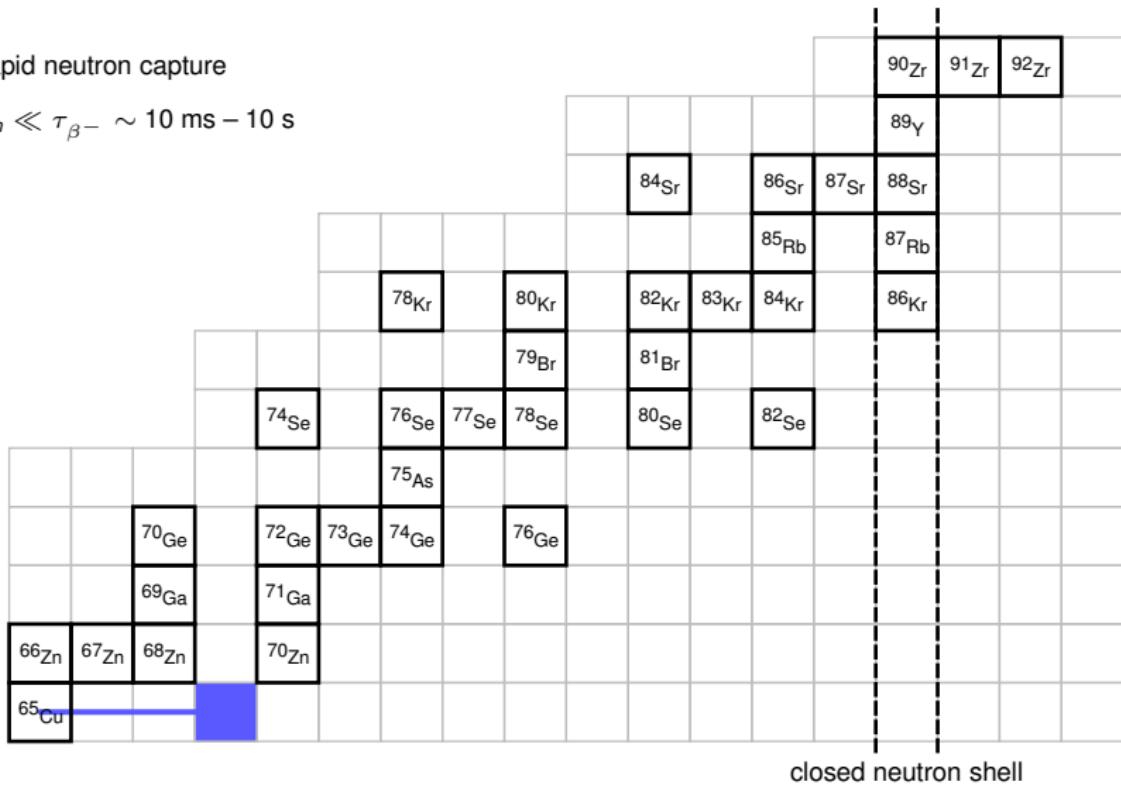
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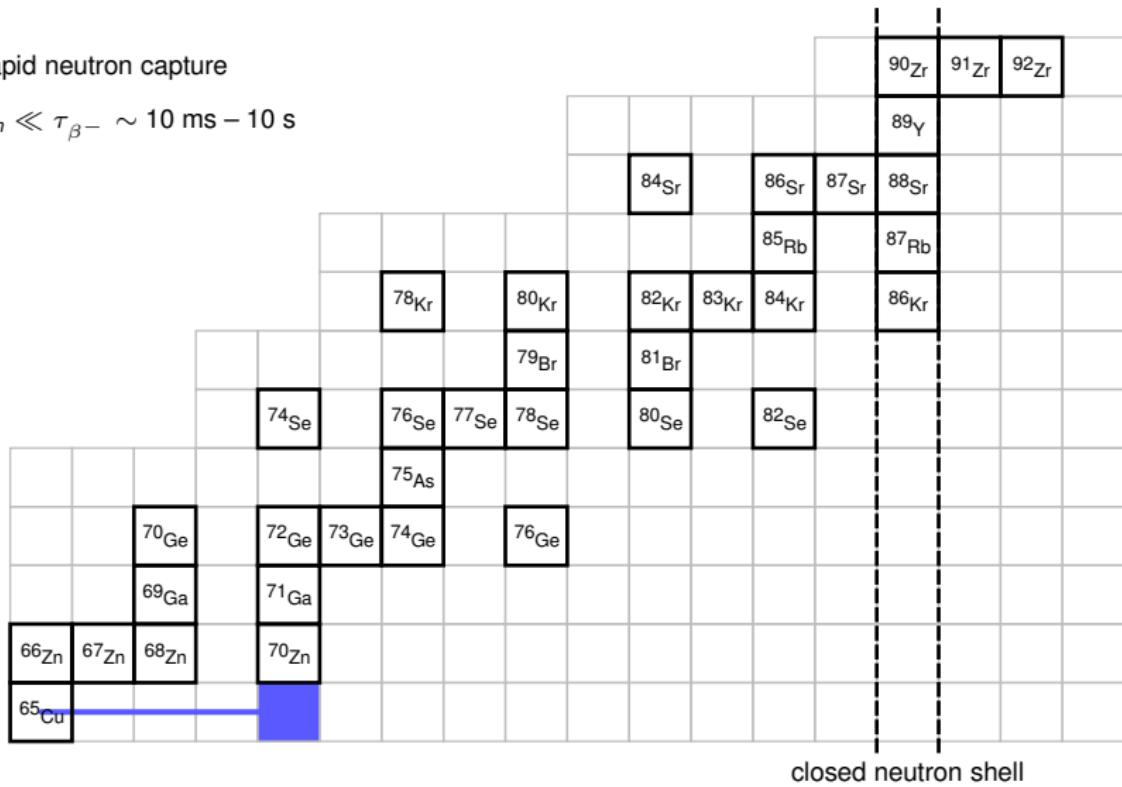
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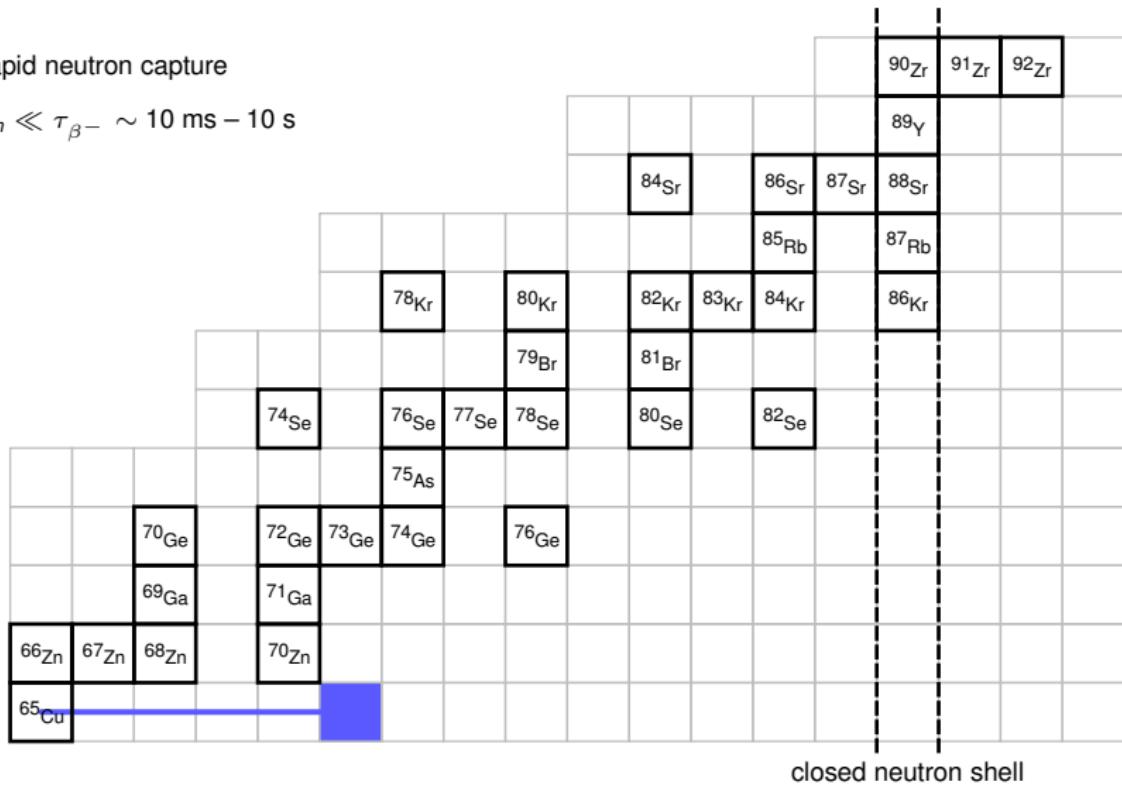
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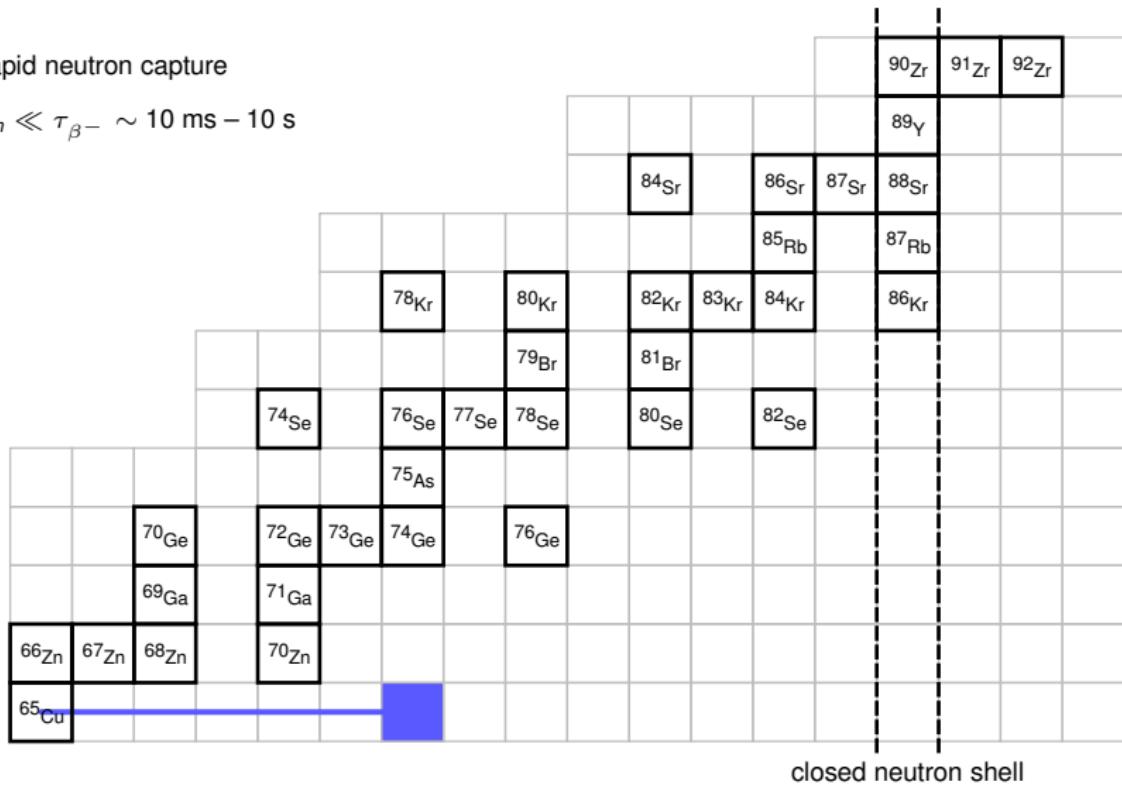


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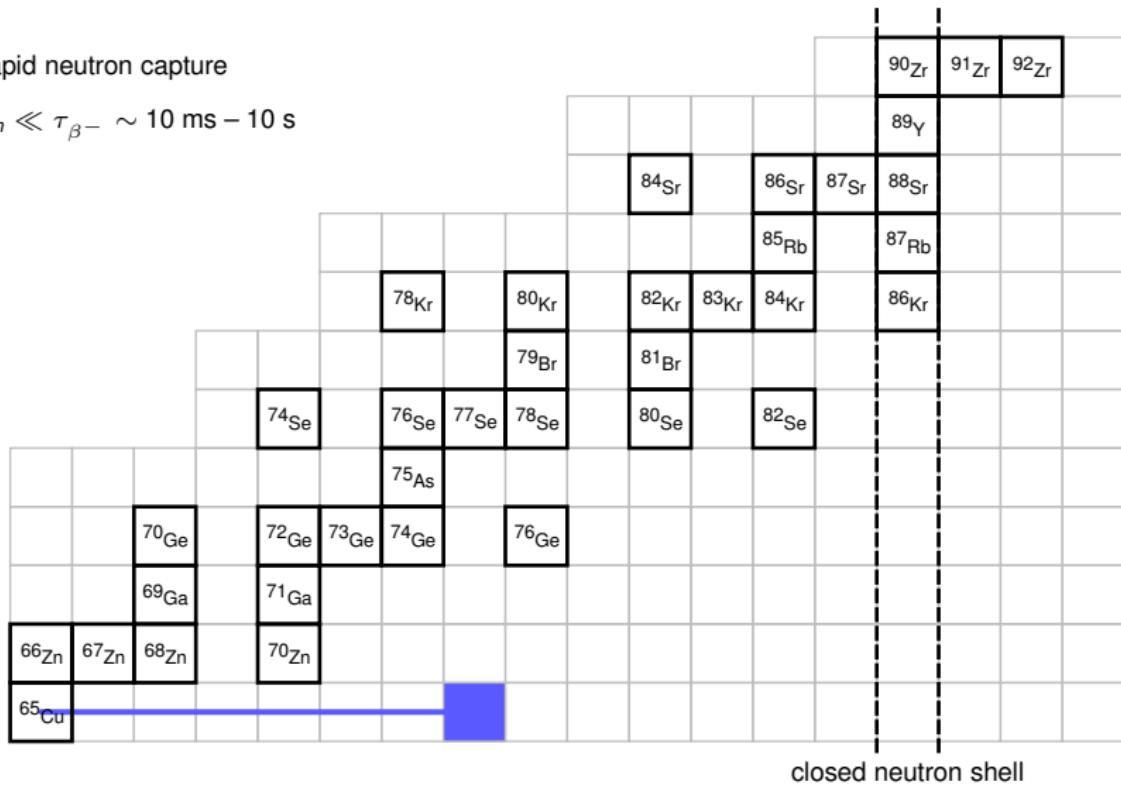


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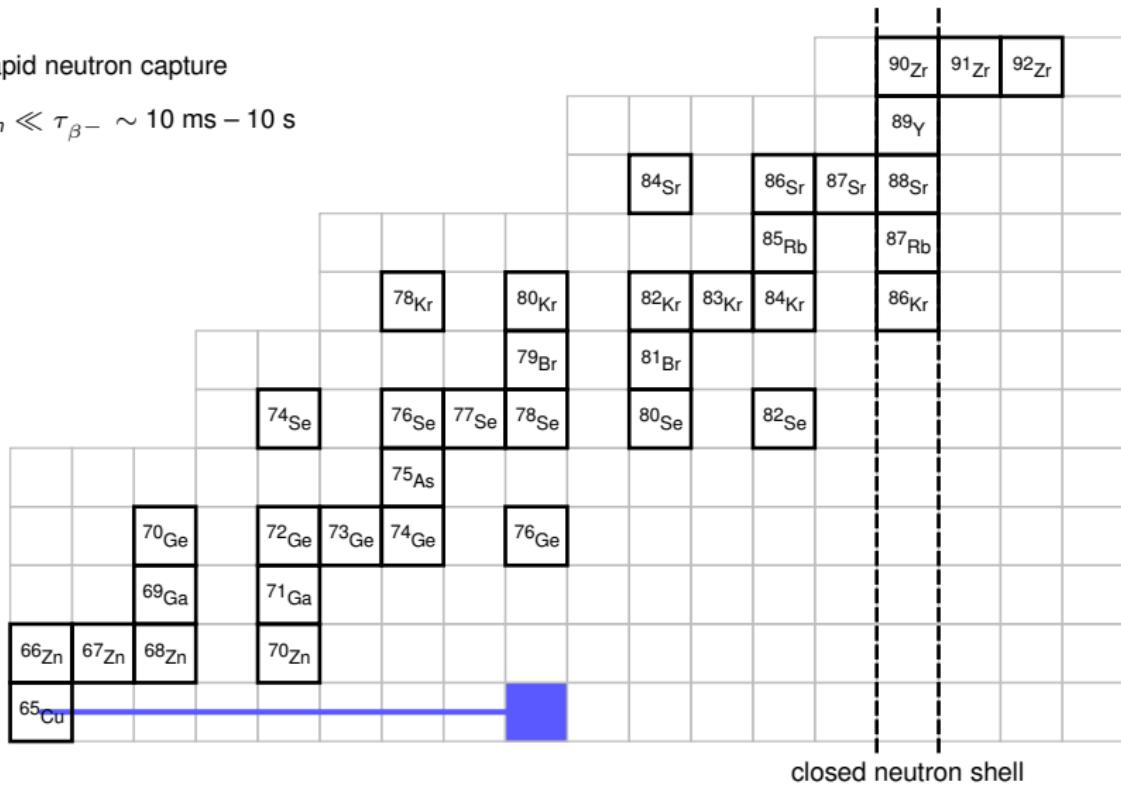


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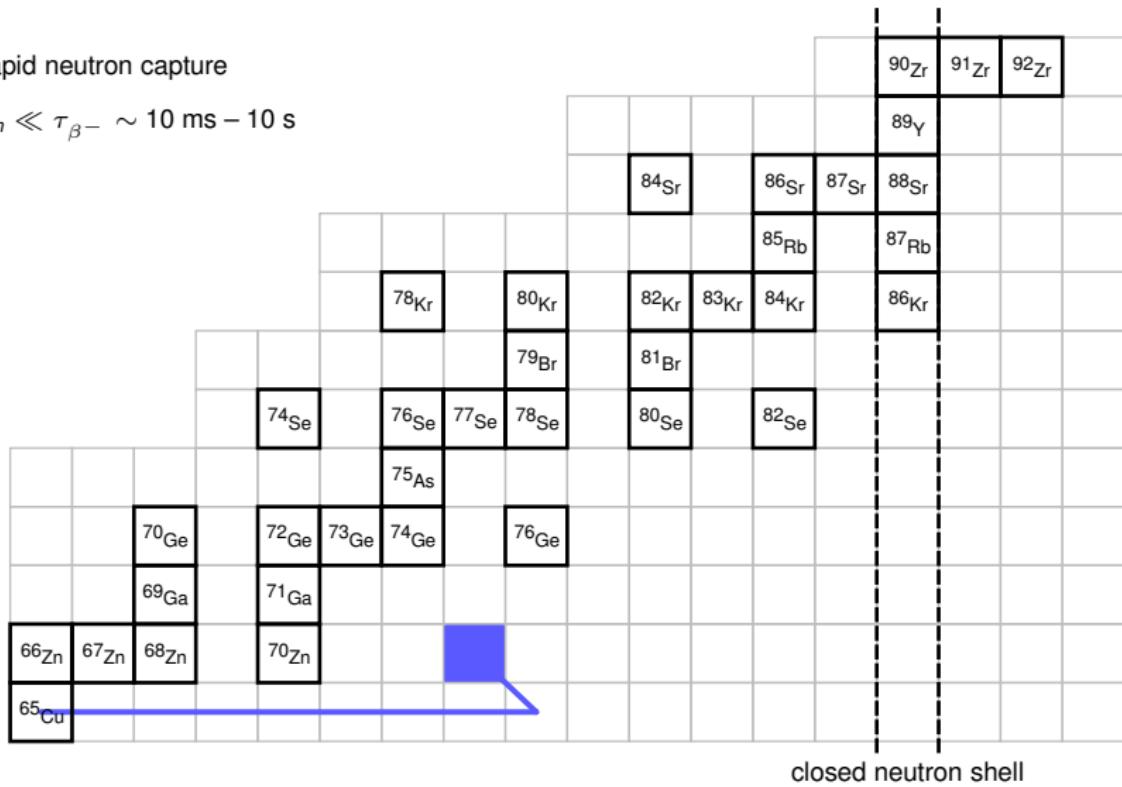


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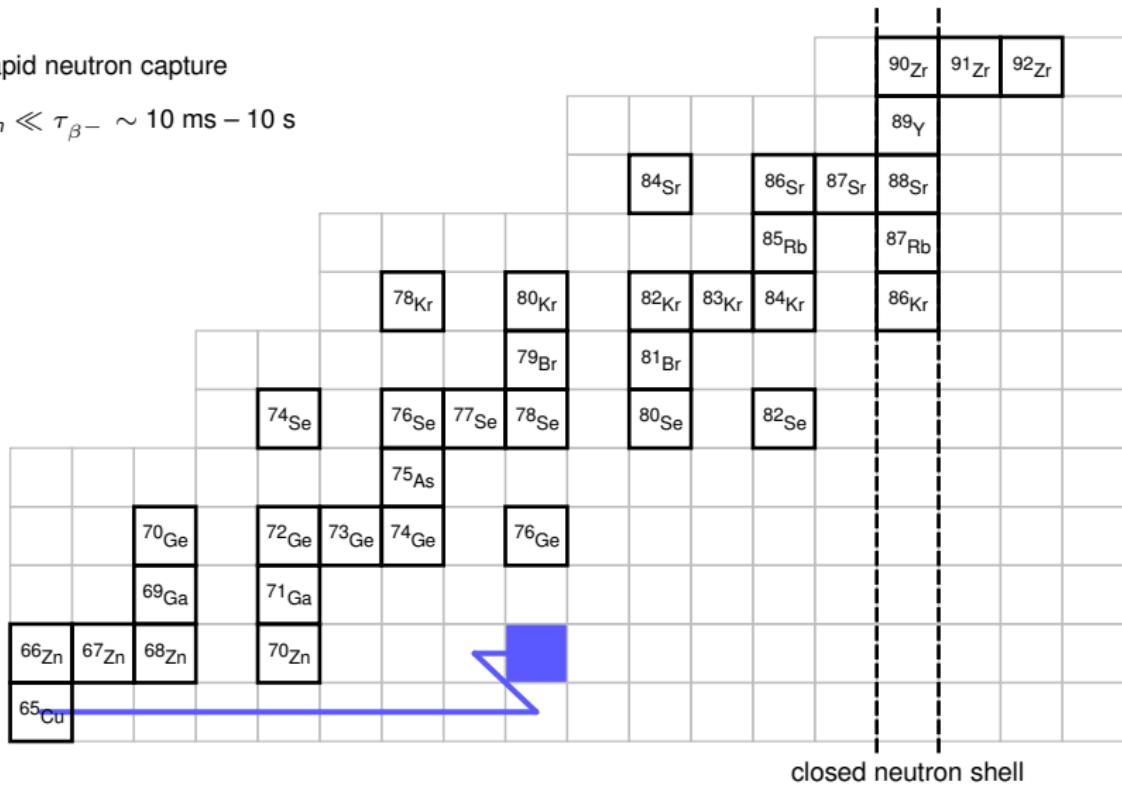
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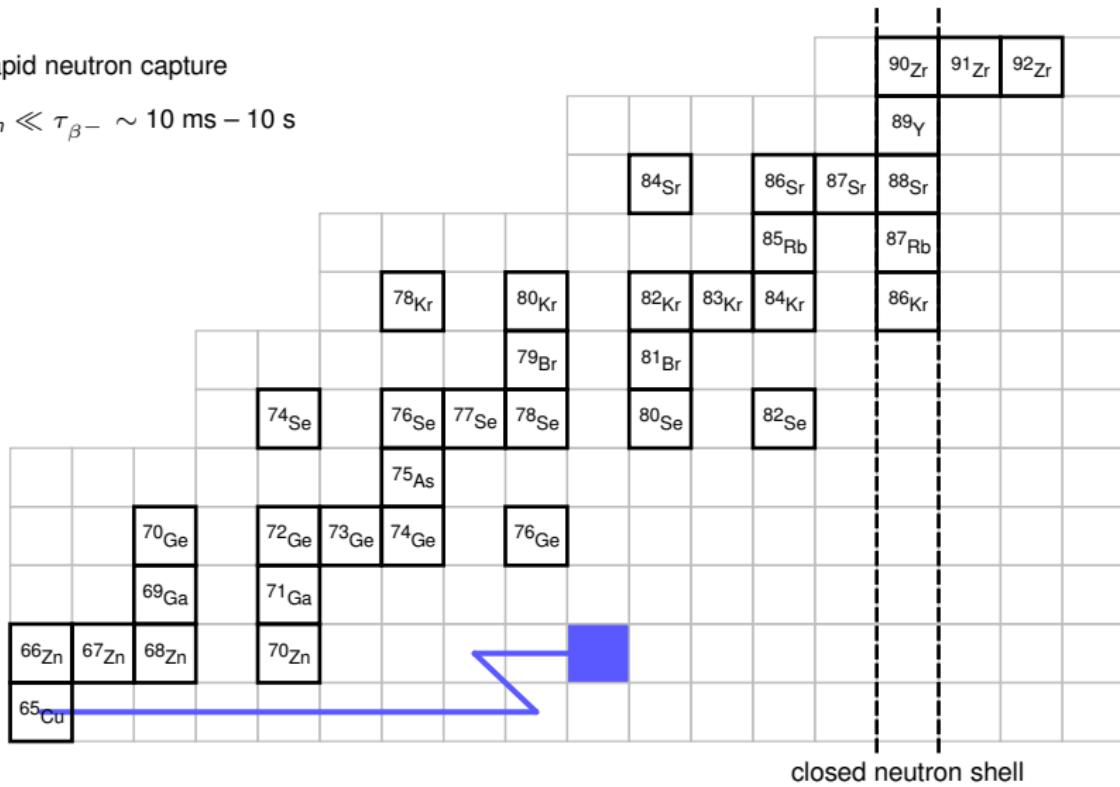


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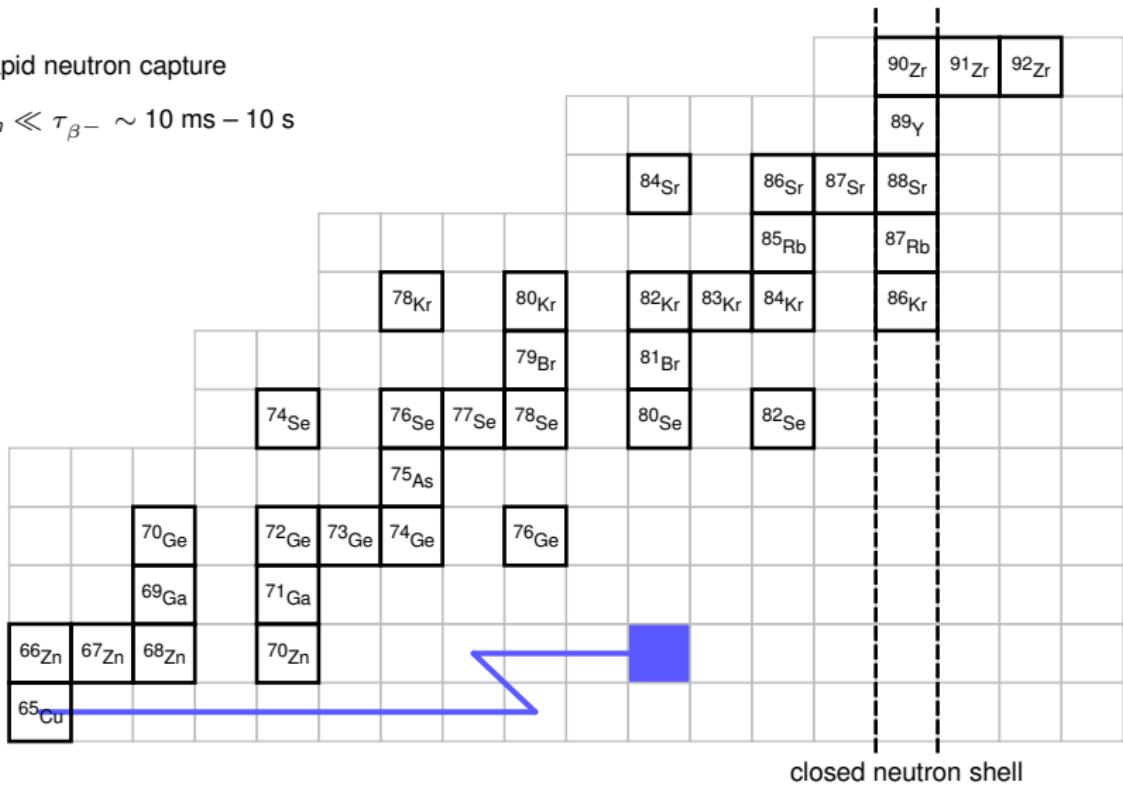
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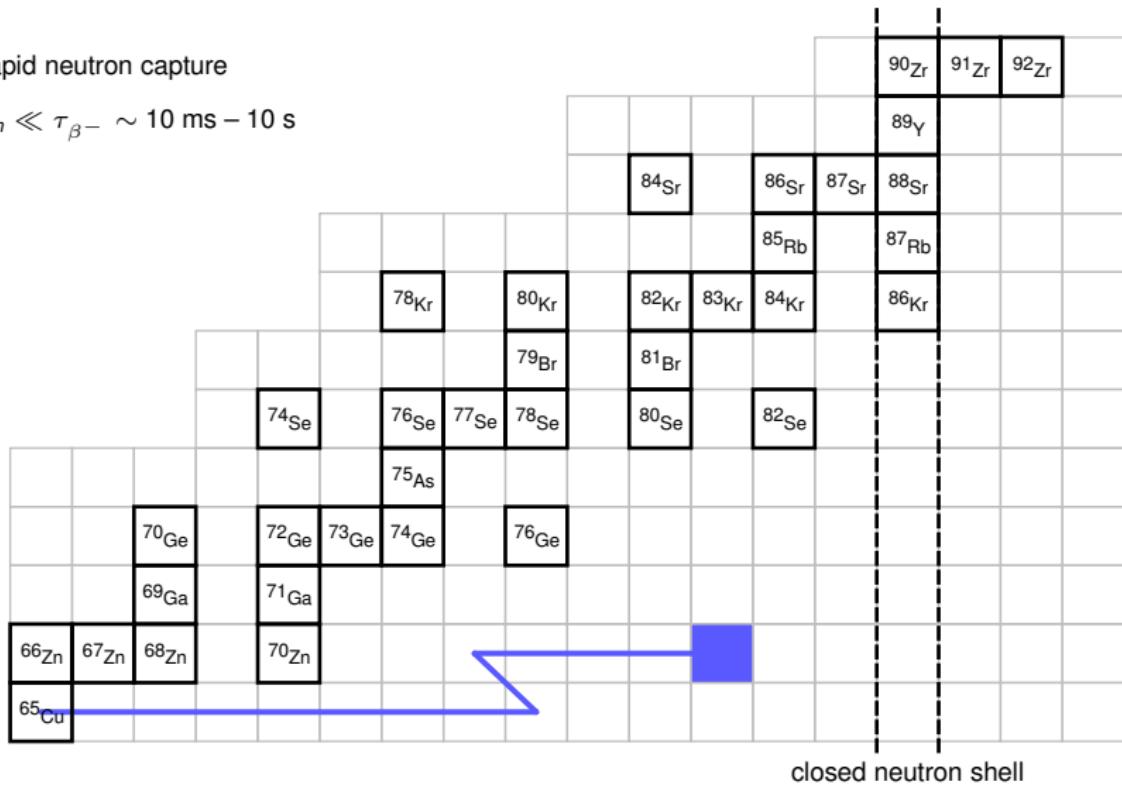


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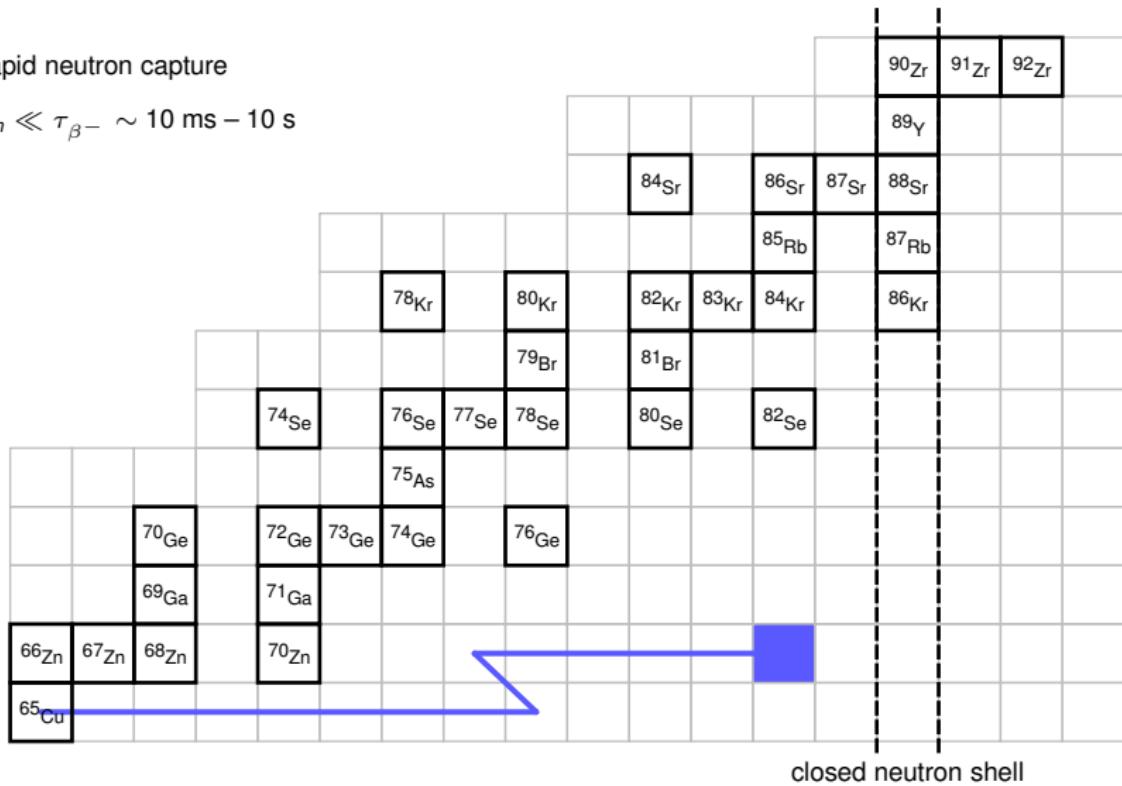


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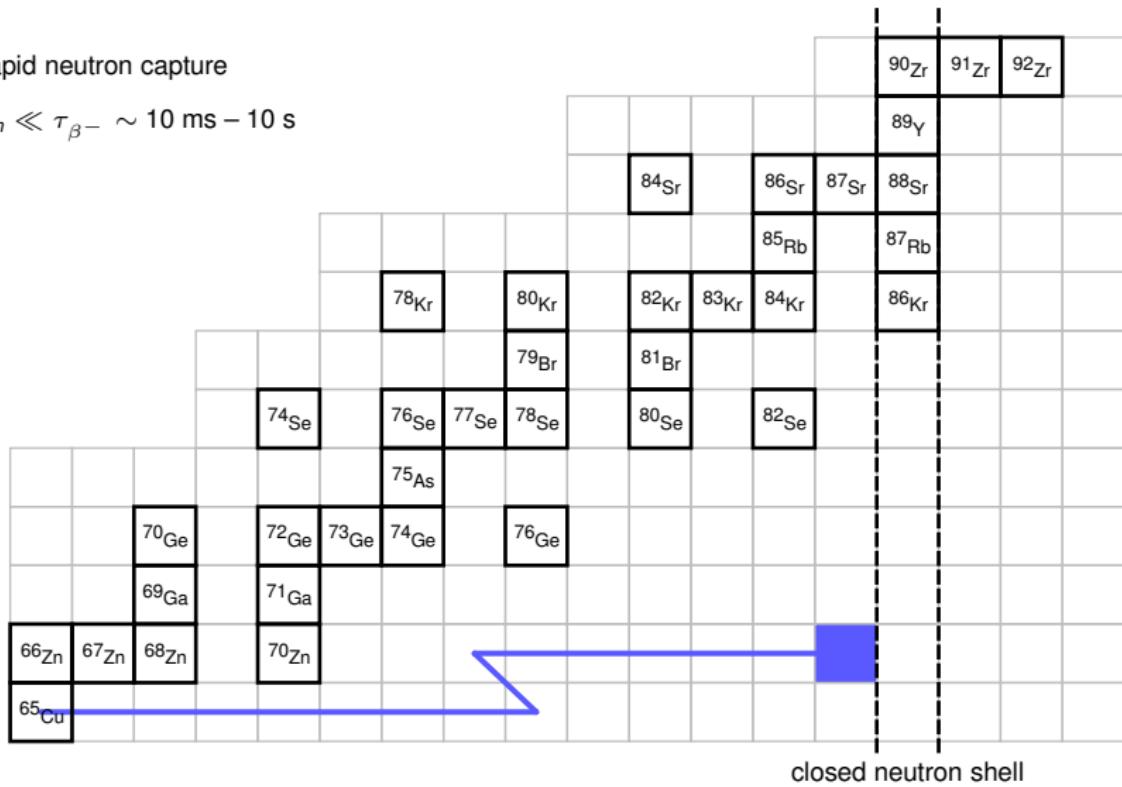
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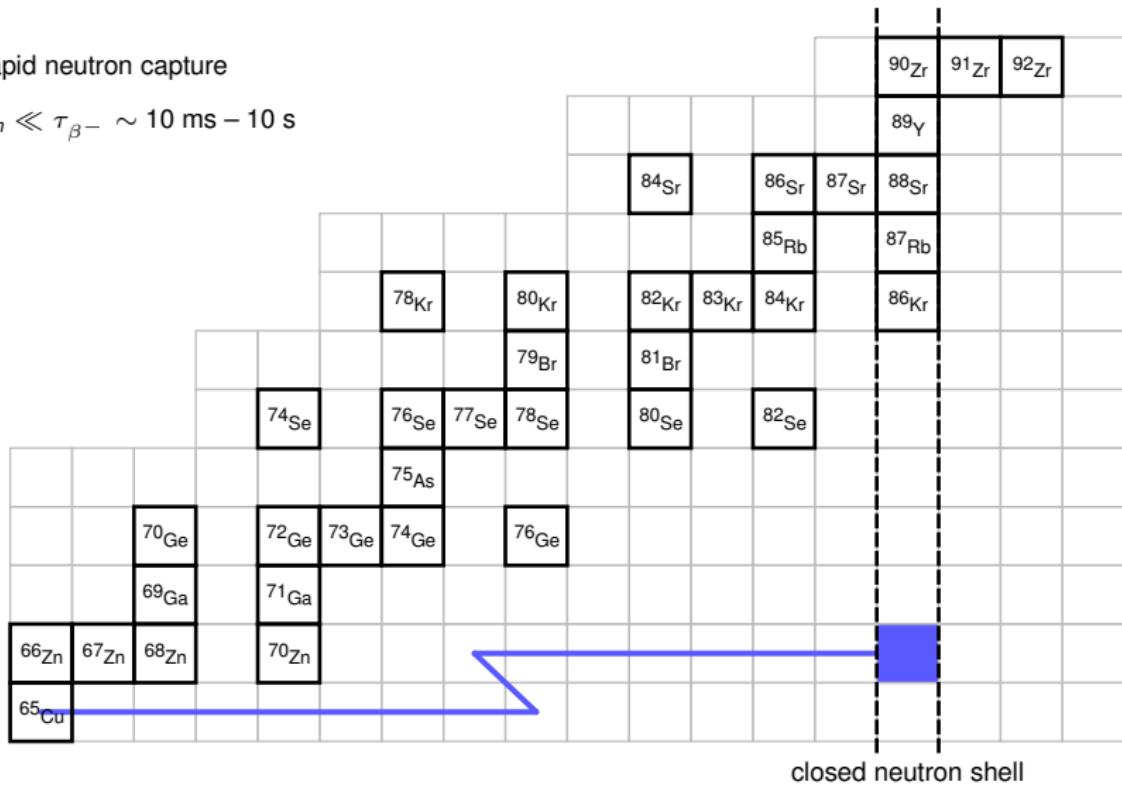
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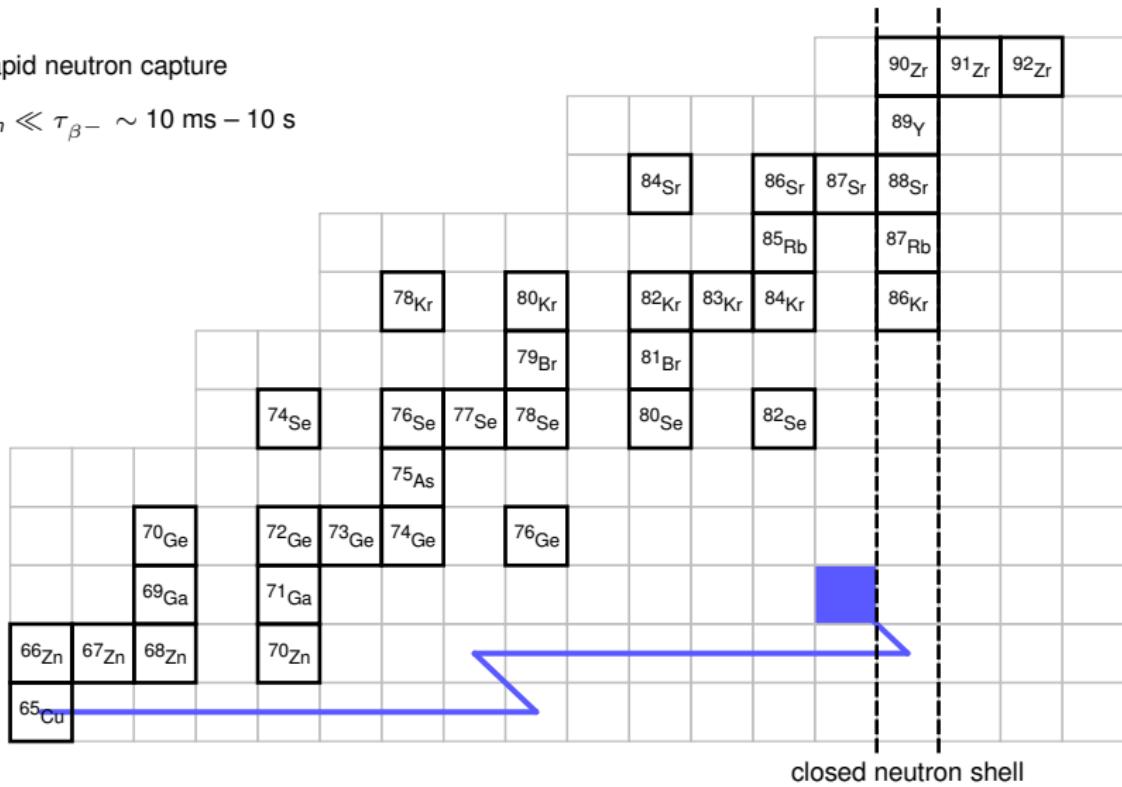
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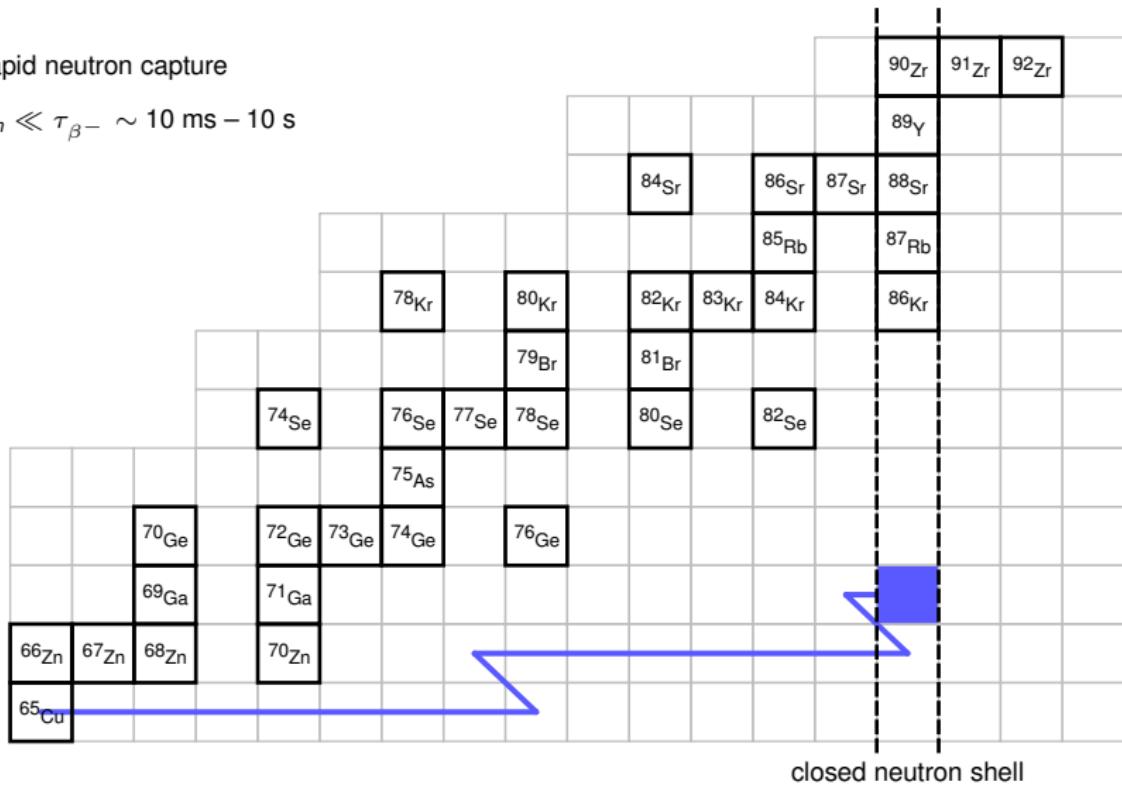


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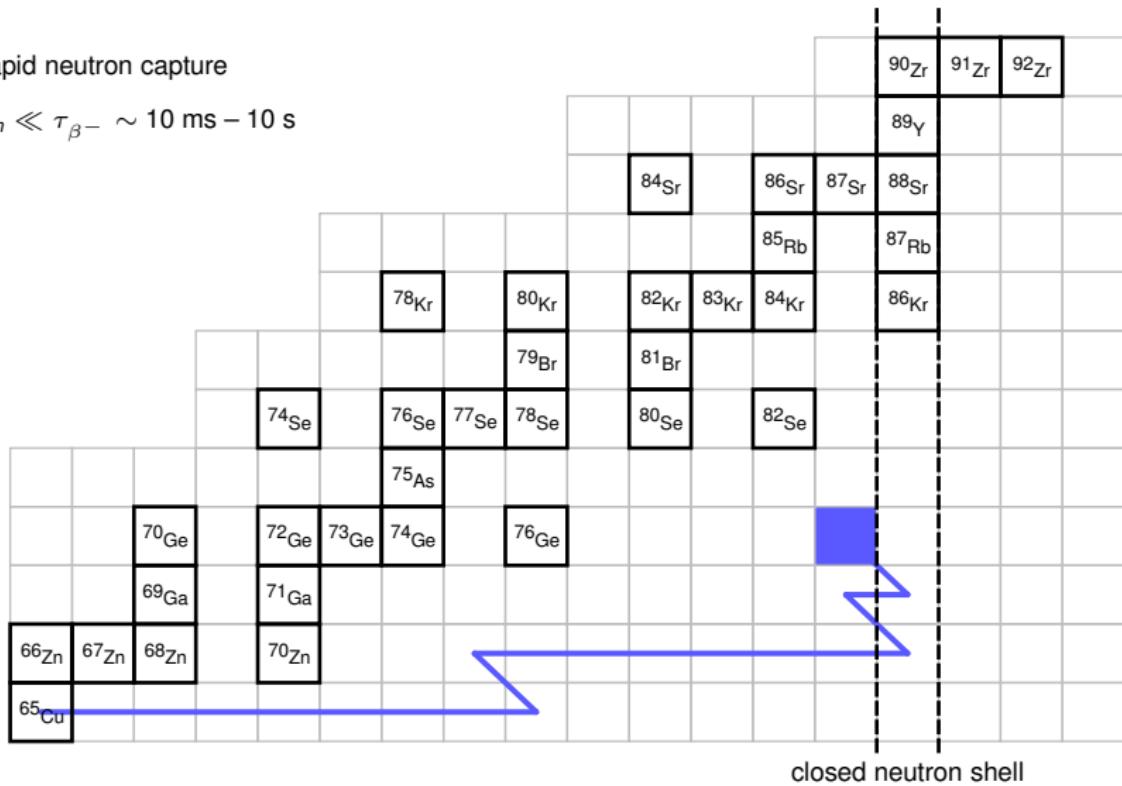


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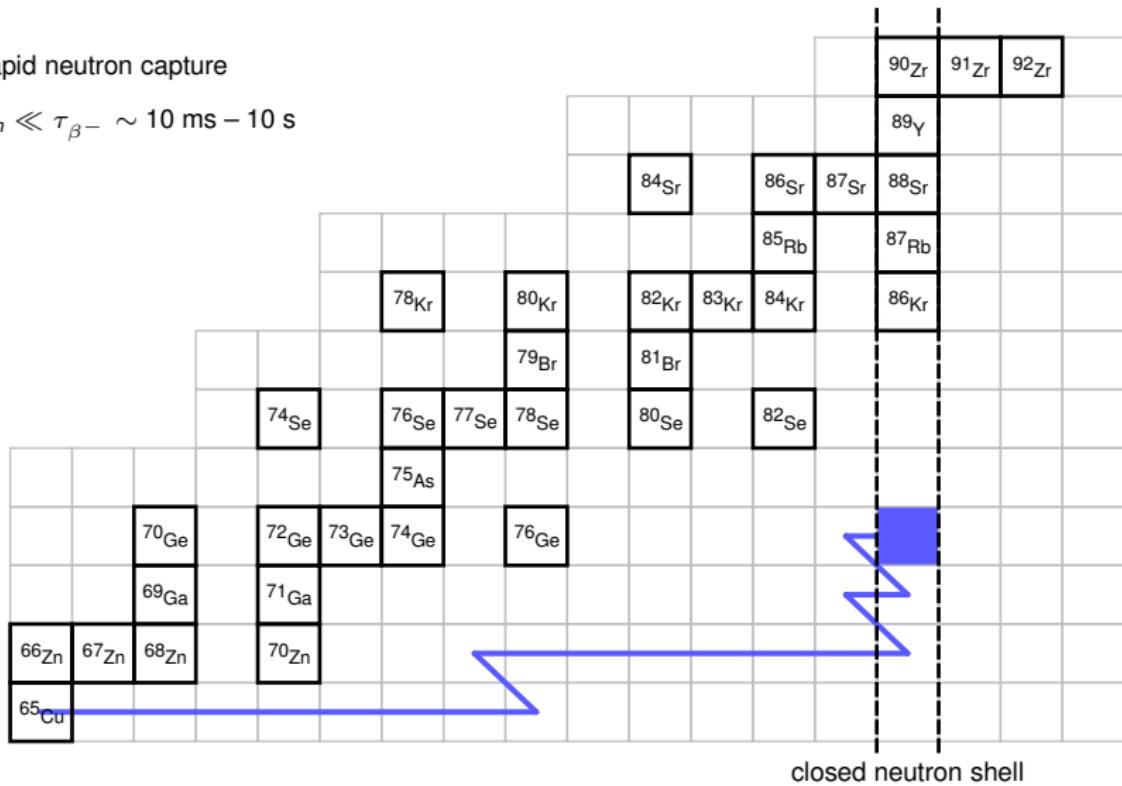


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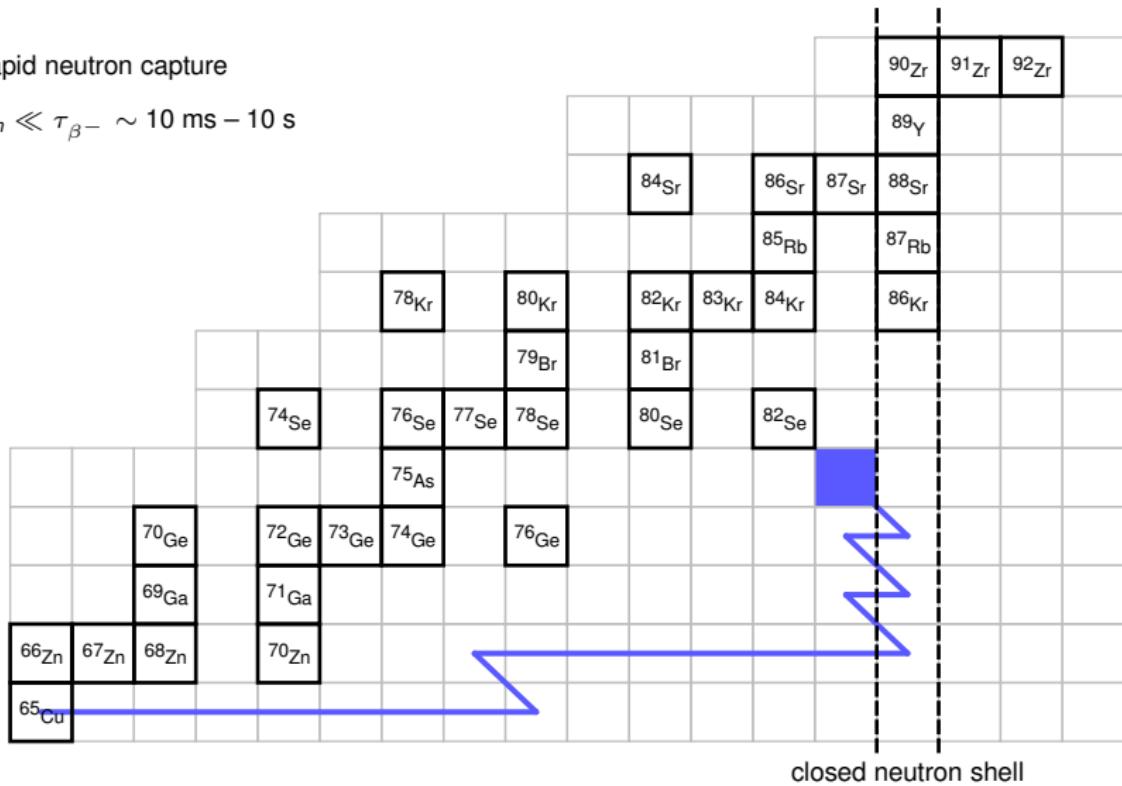


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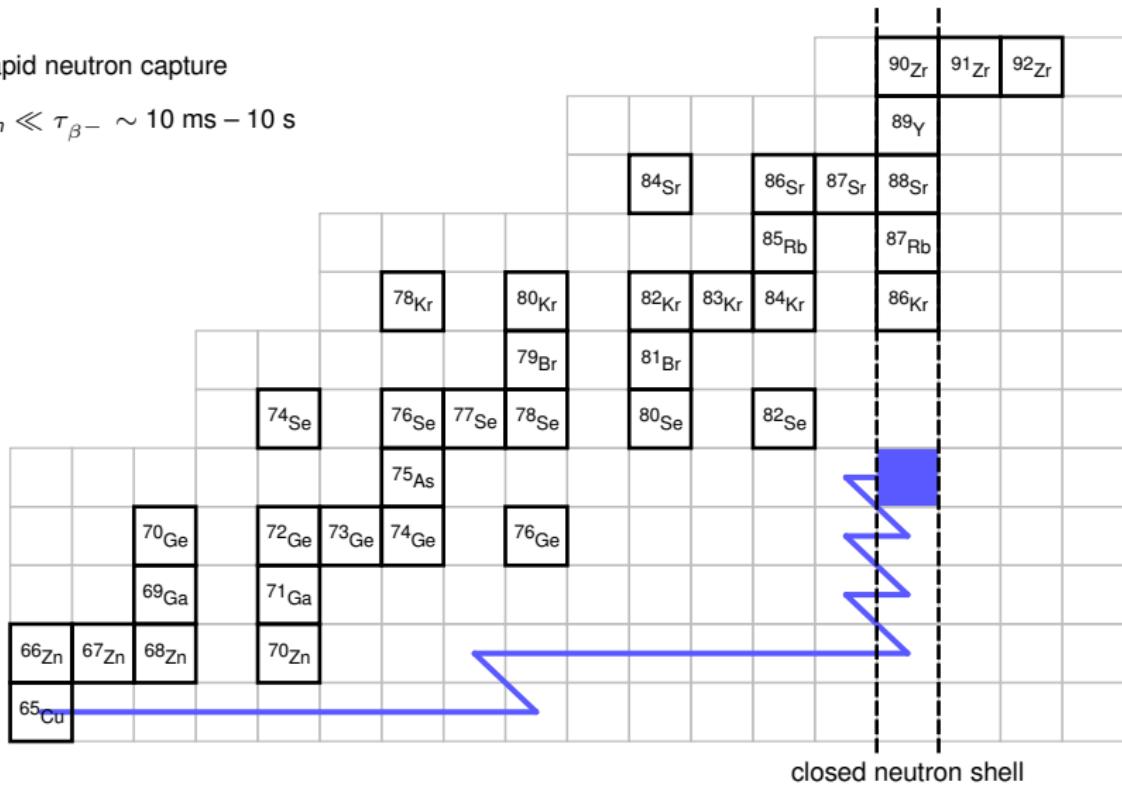


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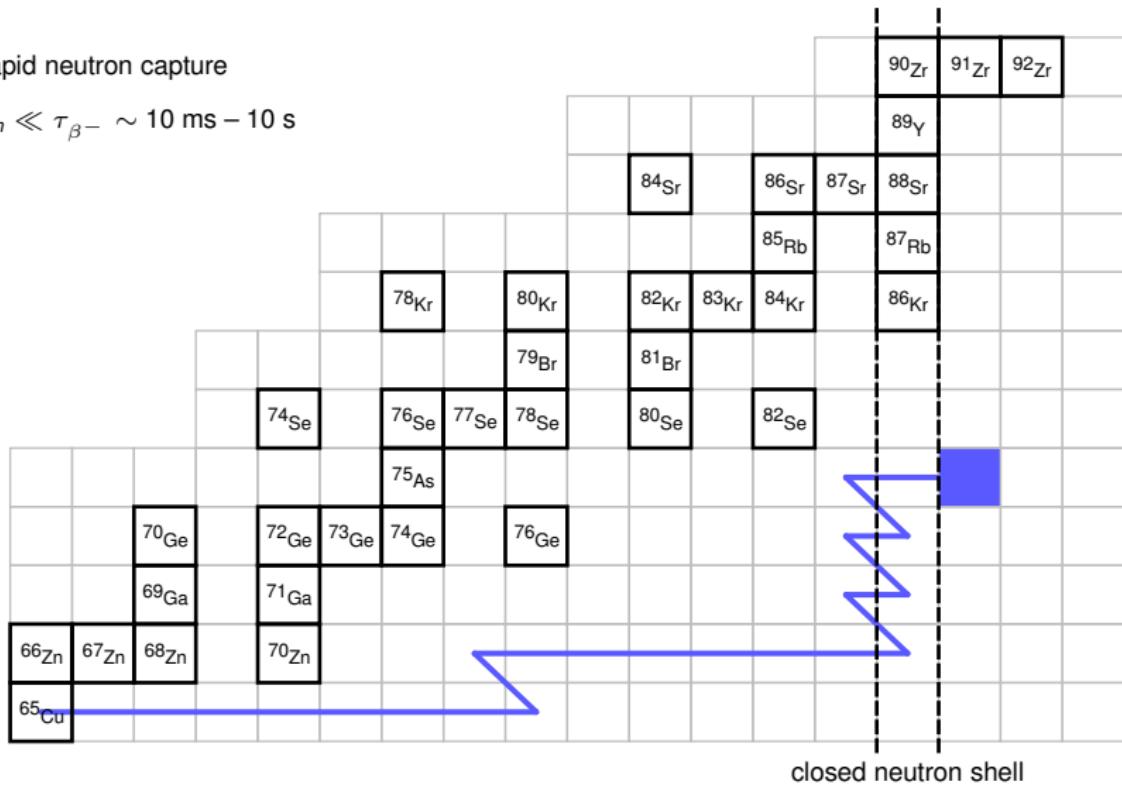


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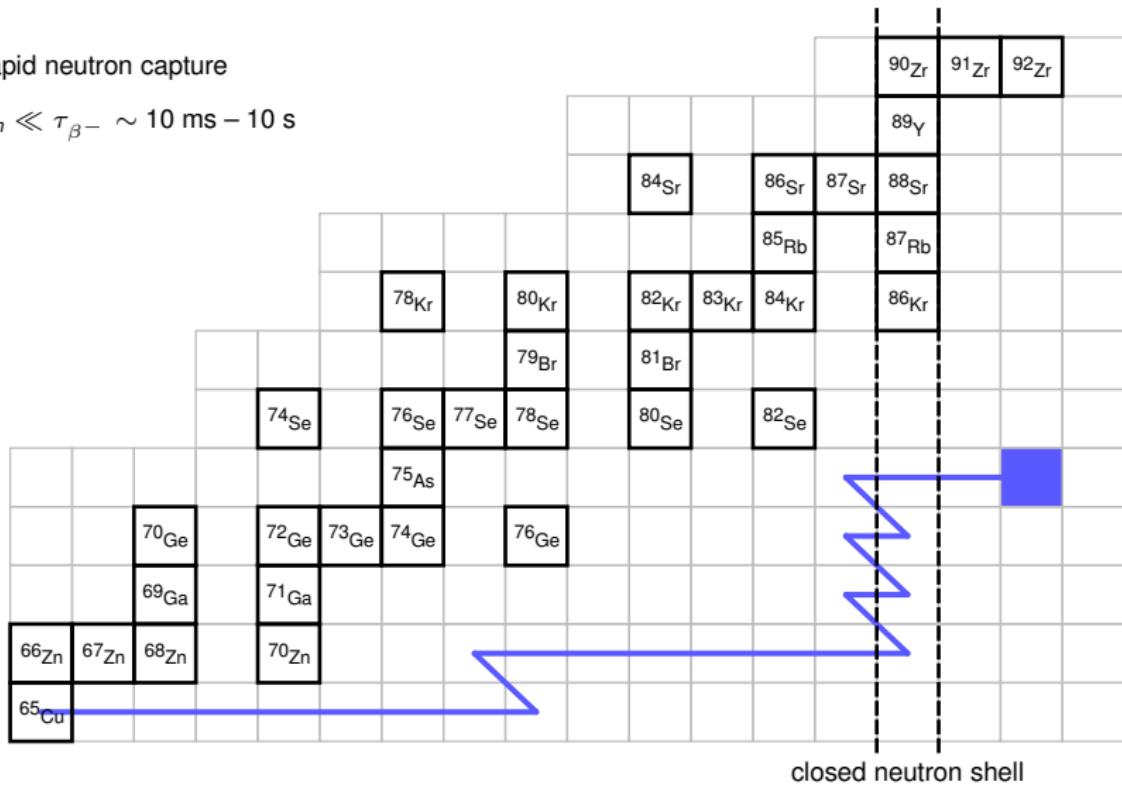
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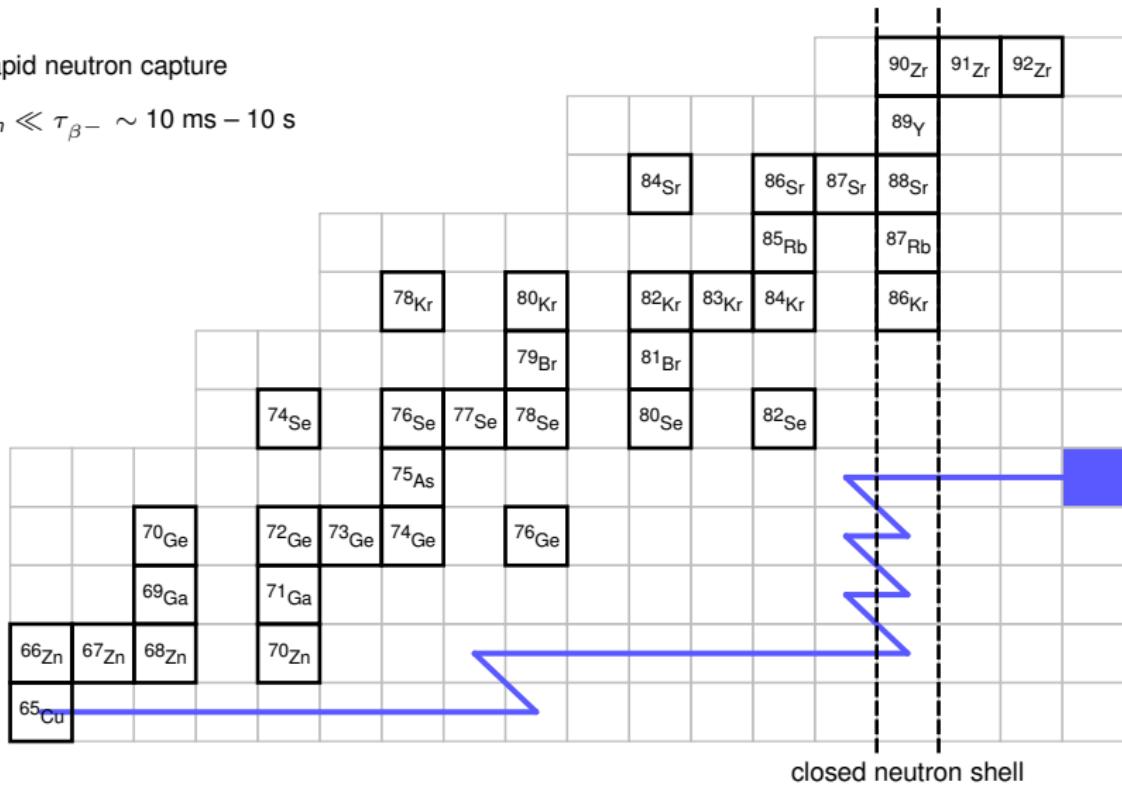


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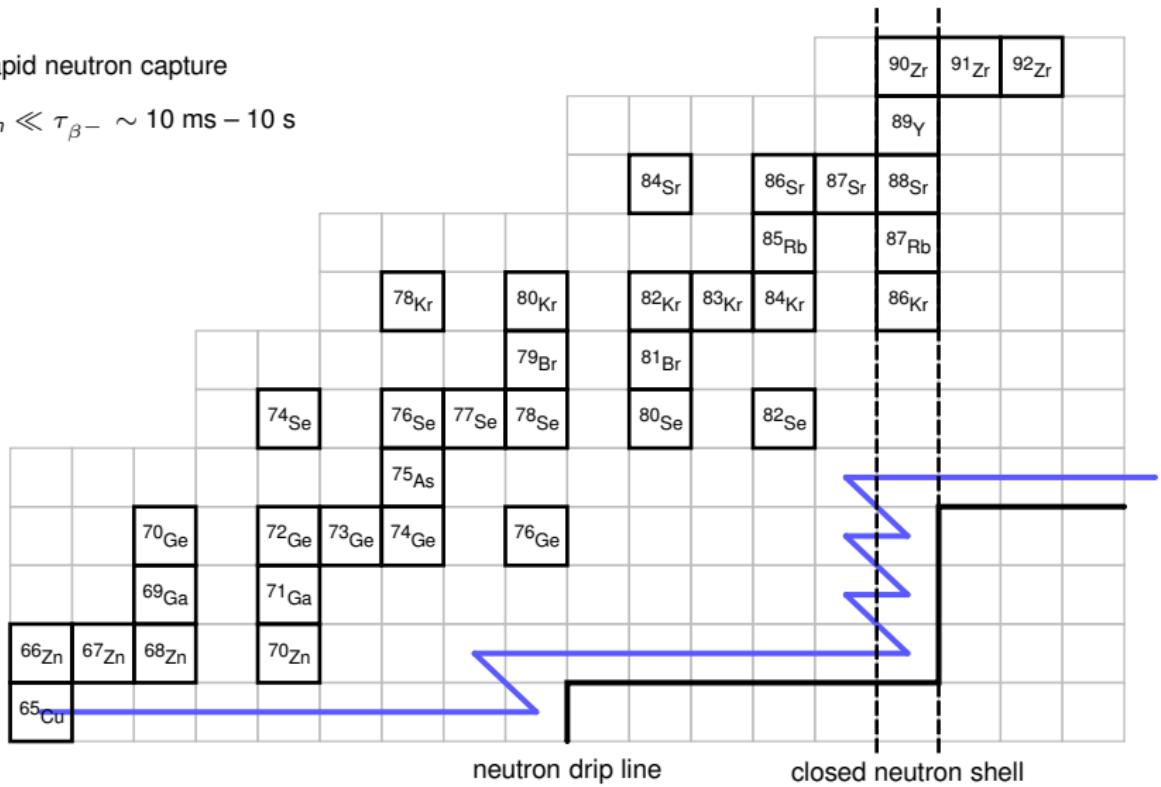


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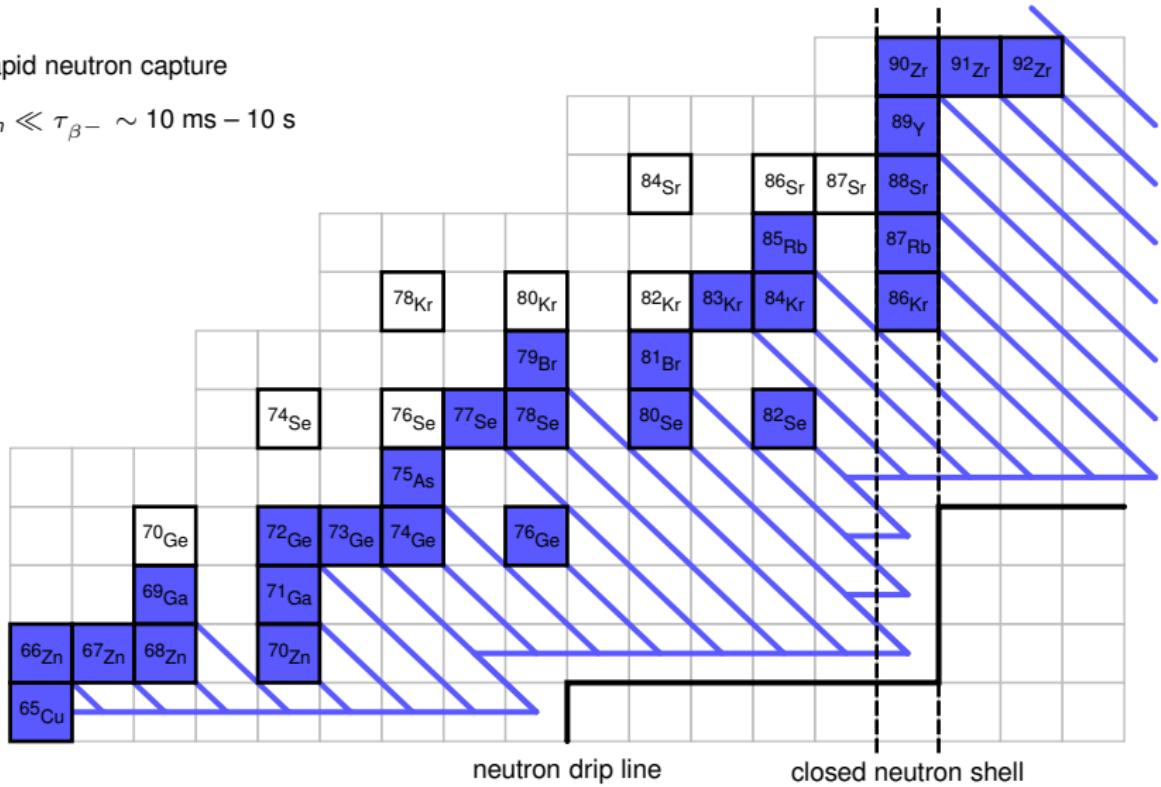
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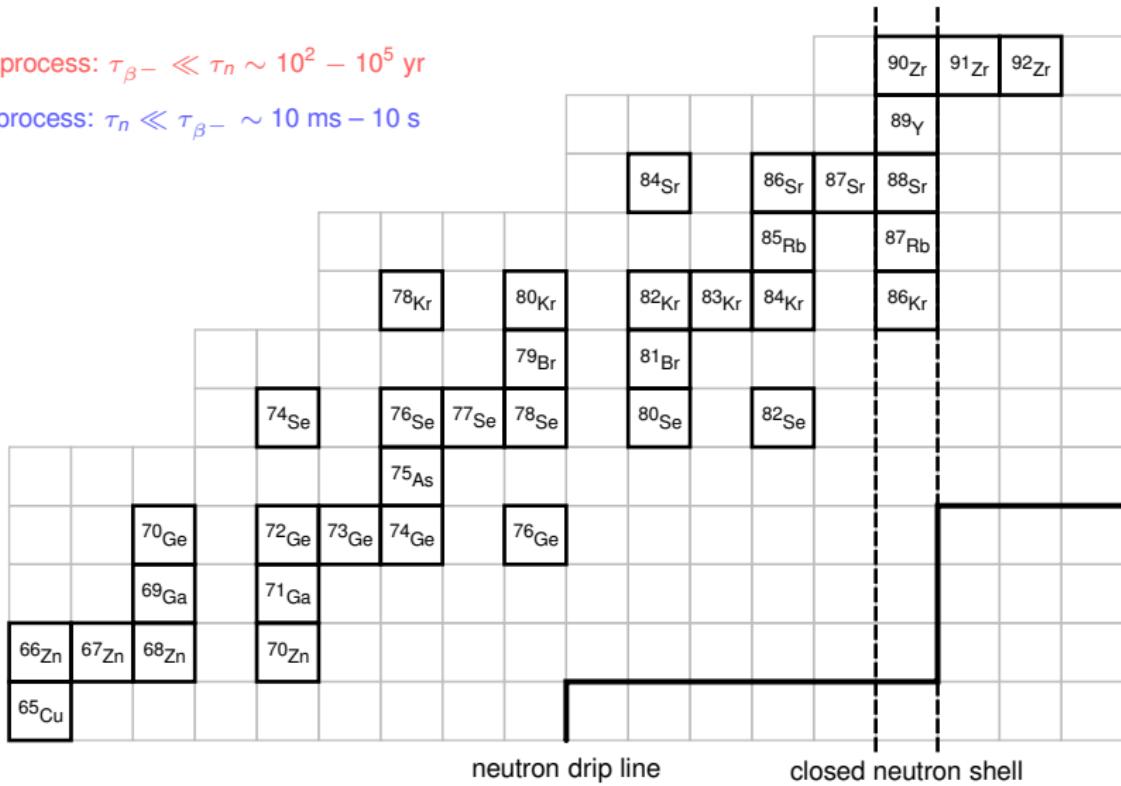
neutron drip line

closed neutron shell

Double peaks due to closed neutron shells

s-process: $\tau_{\beta^-} \ll \tau_n \sim 10^2 - 10^5$ yr

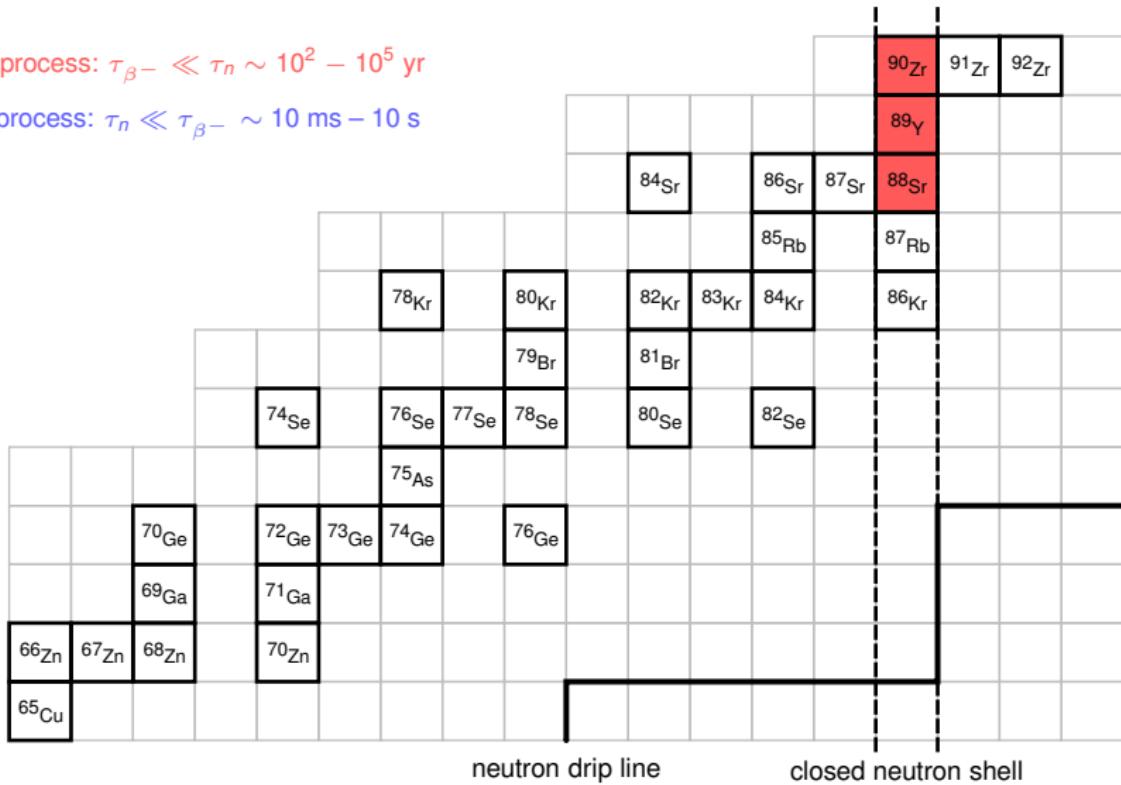
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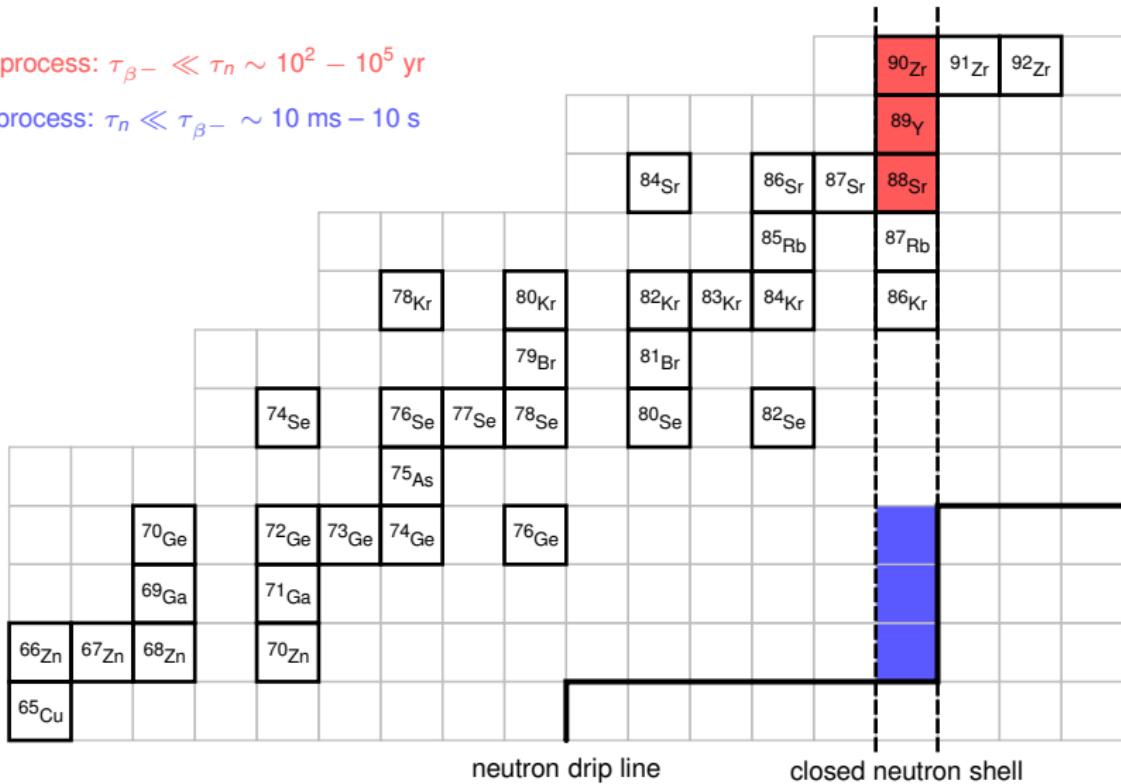
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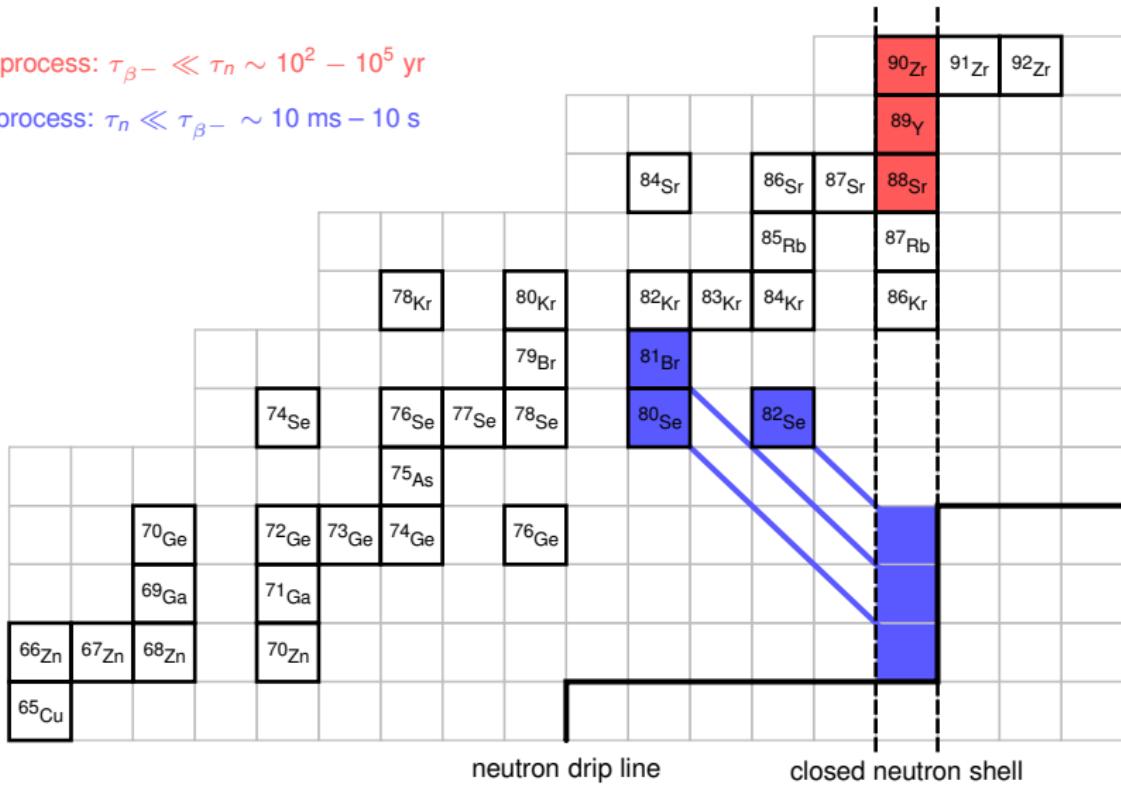
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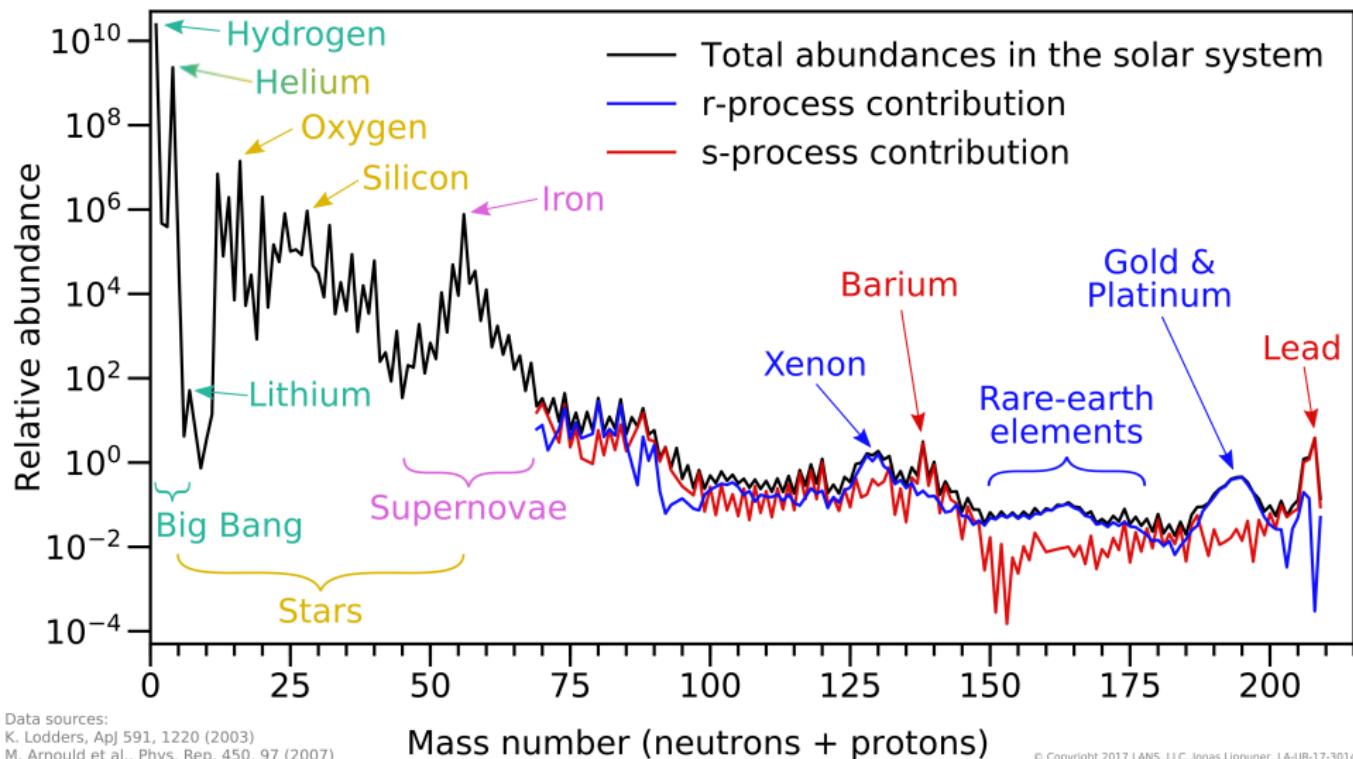
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Solar system abundances



Data sources:
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SkyNet



- General-purpose nuclear reaction network
- ~ 8000 isotopes, $\sim 140,000$ nuclear reactions
- Evolves temperature based on nuclear reactions
- Input: $\rho(t)$, initial composition, entropy
- Open source

Lippuner, J. and Roberts, L. F., ApJS 233, 18 (2017)

SkyNet features

Science

- Extended Timmes equation of state (EOS)
- Calculate nuclear statistical equilibrium (NSE)
- NSE evolution mode
- Calculate inverse rates from *detailed balance* to be consistent with NSE
- Electron screening with smooth transition between weak and strong screening (reactions and NSE)

Code

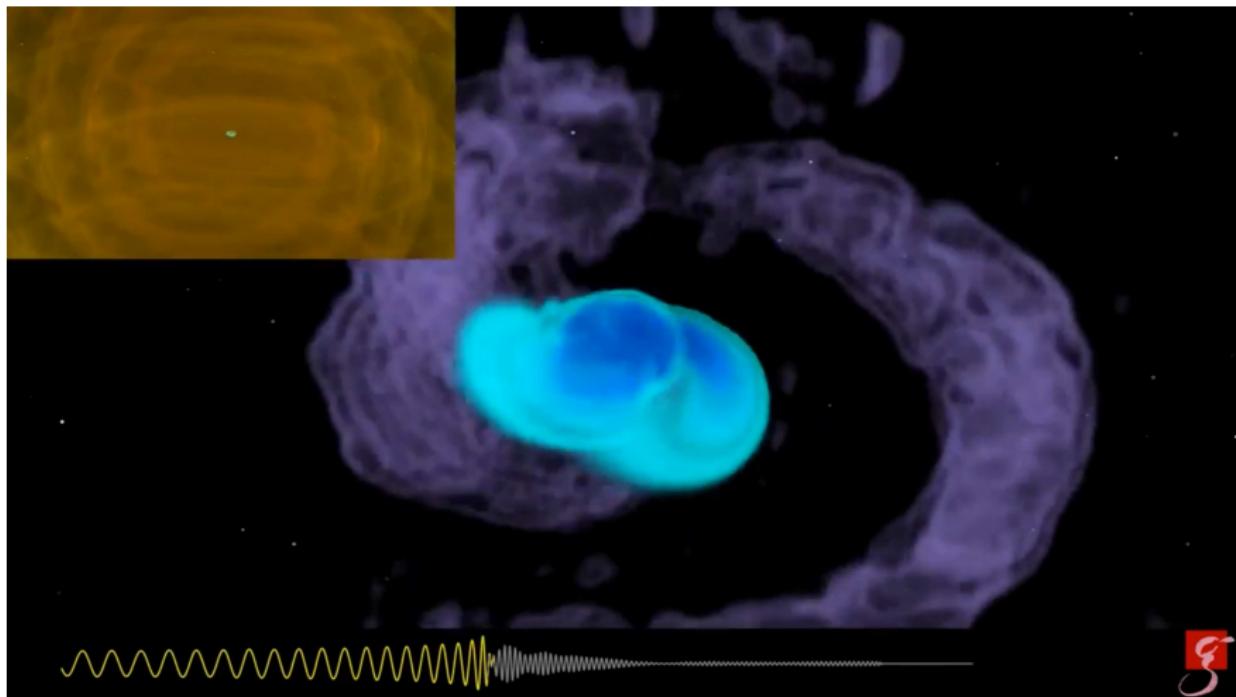
- Adaptive time stepping
- Python bindings
- Modularity
- Extendible reaction class (currently REACLIB, table, neutrino)
- Make movies

Outline

1. r-Process nucleosynthesis overview
2. **r-Process in neutron star mergers**
3. Observational signature and first detection

Neutron star merger ejecta

<https://youtu.be/V6cm-0bwJ98>



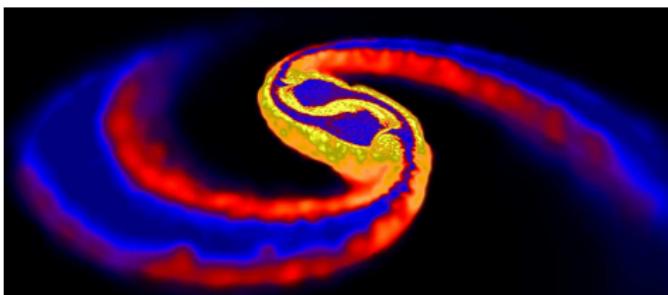
Merger ejecta: Dynamical

Tidal tails or collision interface

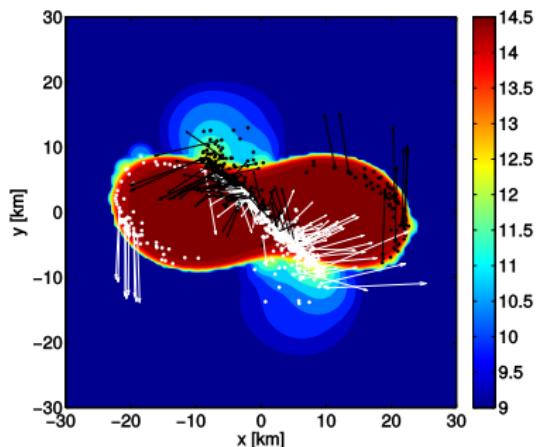
NS–NS: $M_{\text{ej}} \sim 10^{-4} - \text{few} \times 10^{-2} M_{\odot}$, $Y_e \sim 0.05 - 0.45$

NS–BH: $M_{\text{ej}} \sim 0 - 10^{-1} M_{\odot}$, $Y_e \lesssim 0.2$

Bauswein+13, Hotokezaka+13, Foucart+14, Sekiguchi+15, Kyutoku+15, Radice+16



From Price+06



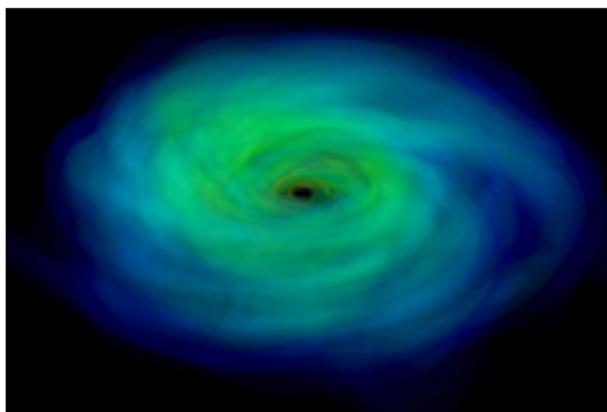
From Bauswein+13

Merger ejecta: Disk outflow

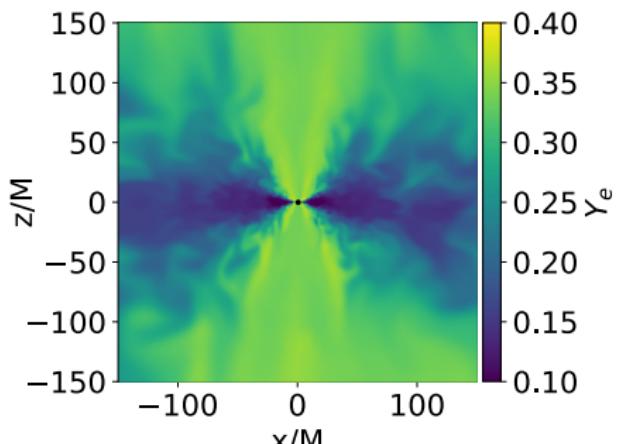
Neutrino-driven wind or outflow due to MHD, viscous heating, and α recombination

$$M_{\text{ej}} \sim \text{few} \times 10^{-3} M_{\odot}, Y_e \sim 0.2 - 0.45$$

Surman+08, Wanajo+11, Fernández+13, Perego+14, Just+15, Foucart+15, Siegel+17, Siegel+18, Miller+19



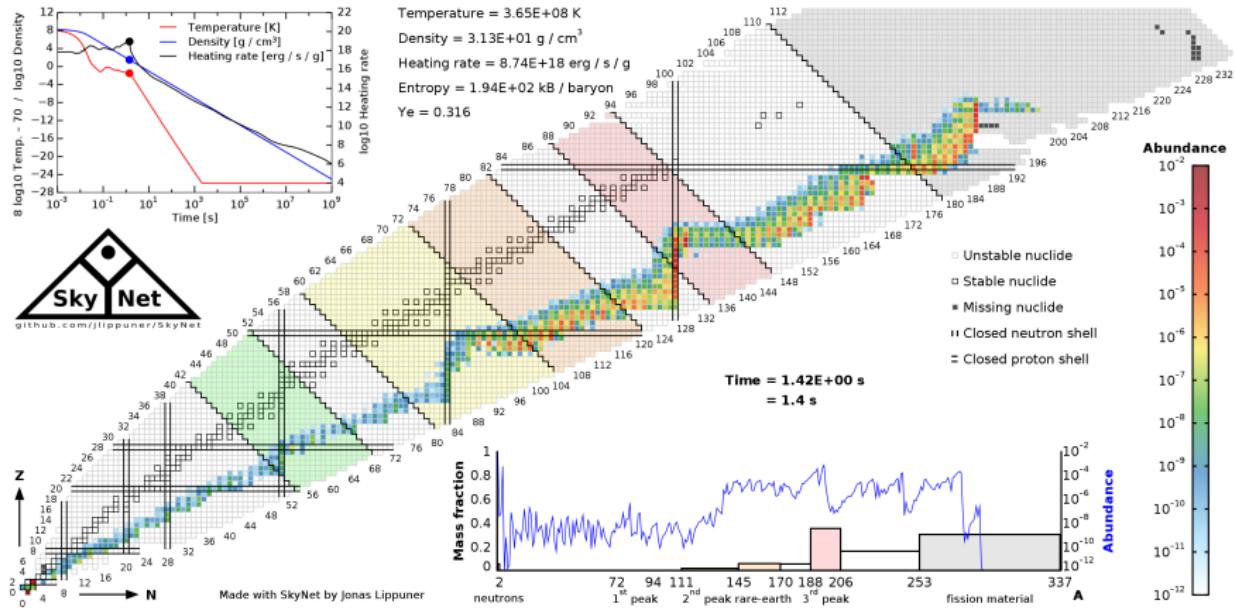
From Miller+19 (in prep)



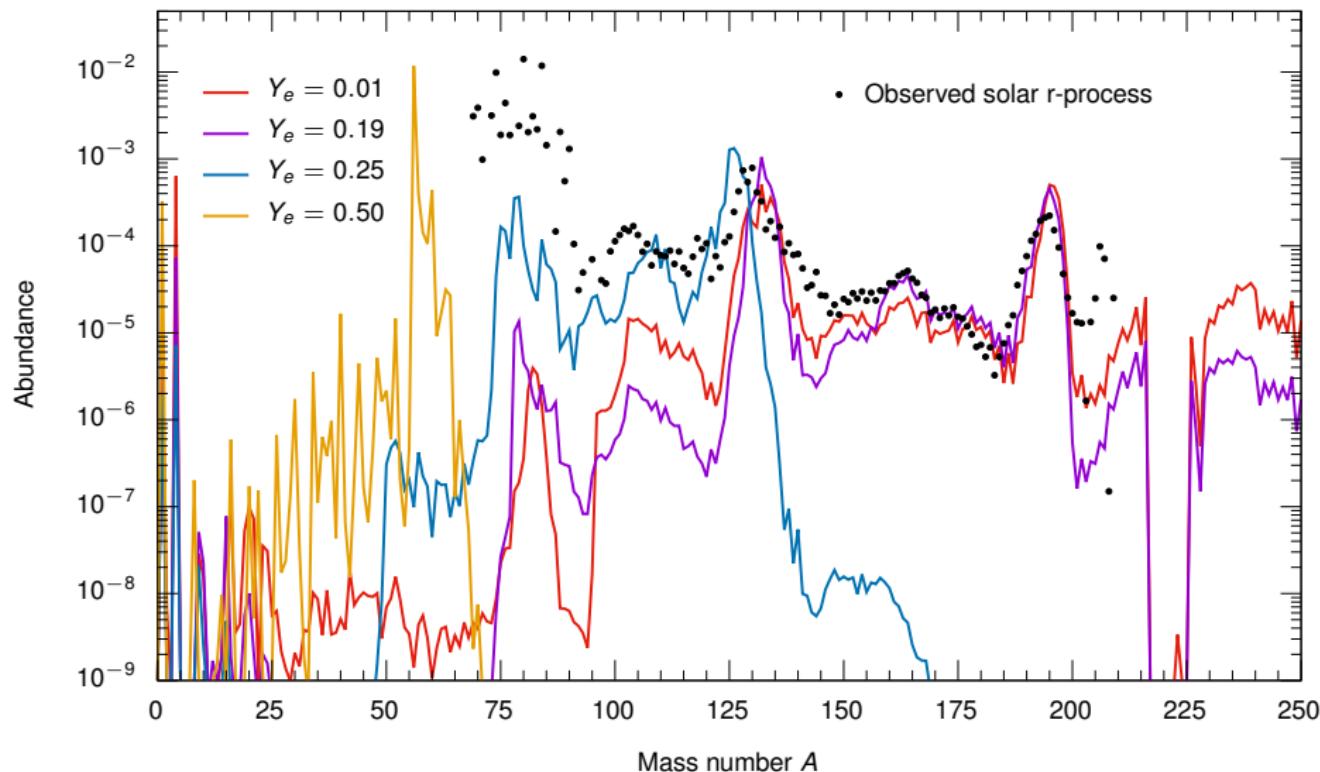
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Movie

http://jonaslippuner.com/skynet/SkyNet_Ye_0.010_s_010.000_tau_007.100.mp4
http://jonaslippuner.com/skynet/SkyNet_Ye_0.250_s_010.000_tau_007.100.mp4

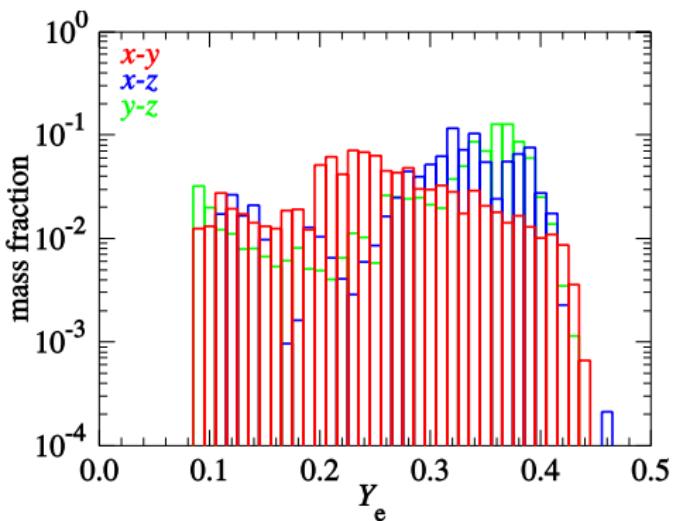


r-Process abundances vs. electron fraction



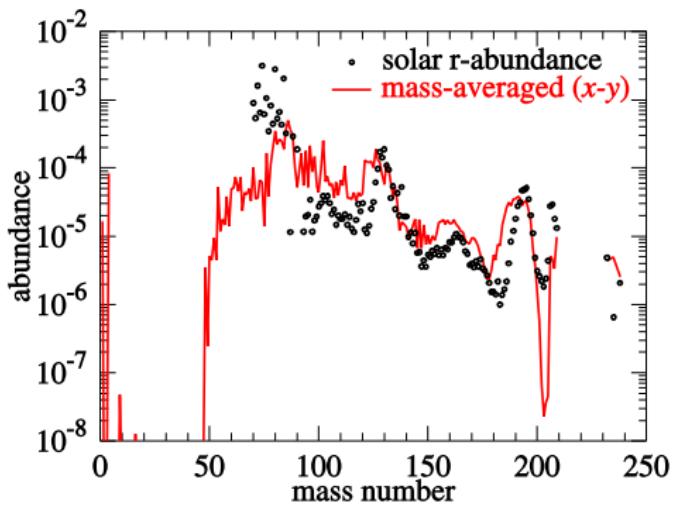
JL, Roberts 2015, ApJ 815, 82, arXiv:1508.03133

Full binary neutron star merger simulations



From Wanajo+14

See also Goriely+15



From Wanajo+14

Nucleosynthesis in HMNS disk outflow

- $3 M_{\odot}$ central HMNS or BH, $0.03 M_{\odot}$ accretion disk
- Variable HMNS lifetime, neutrino leakage, α viscosity

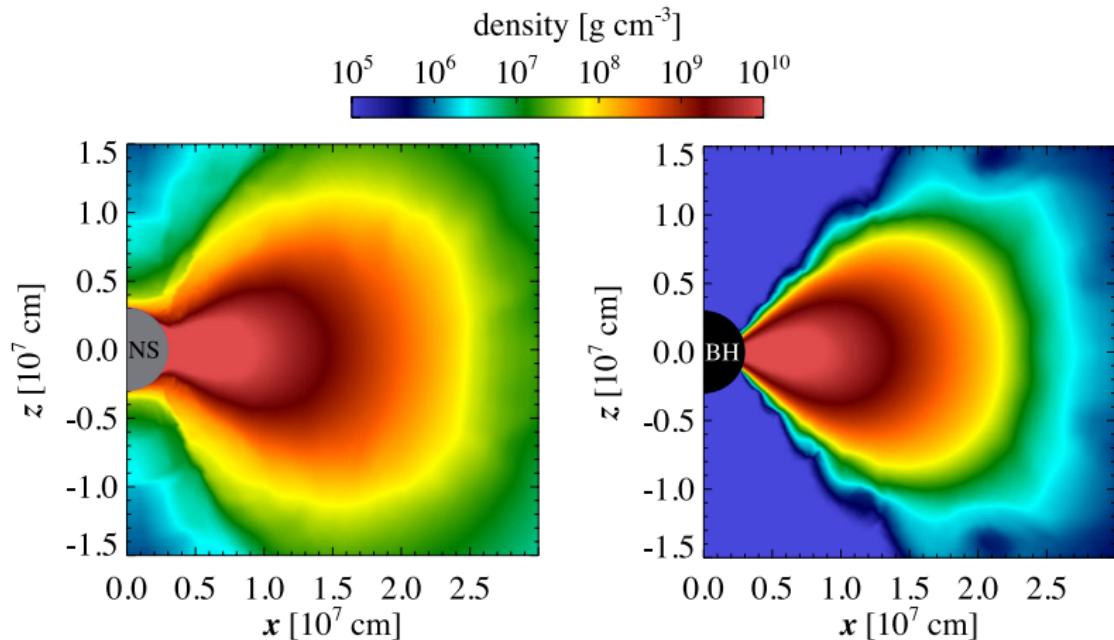
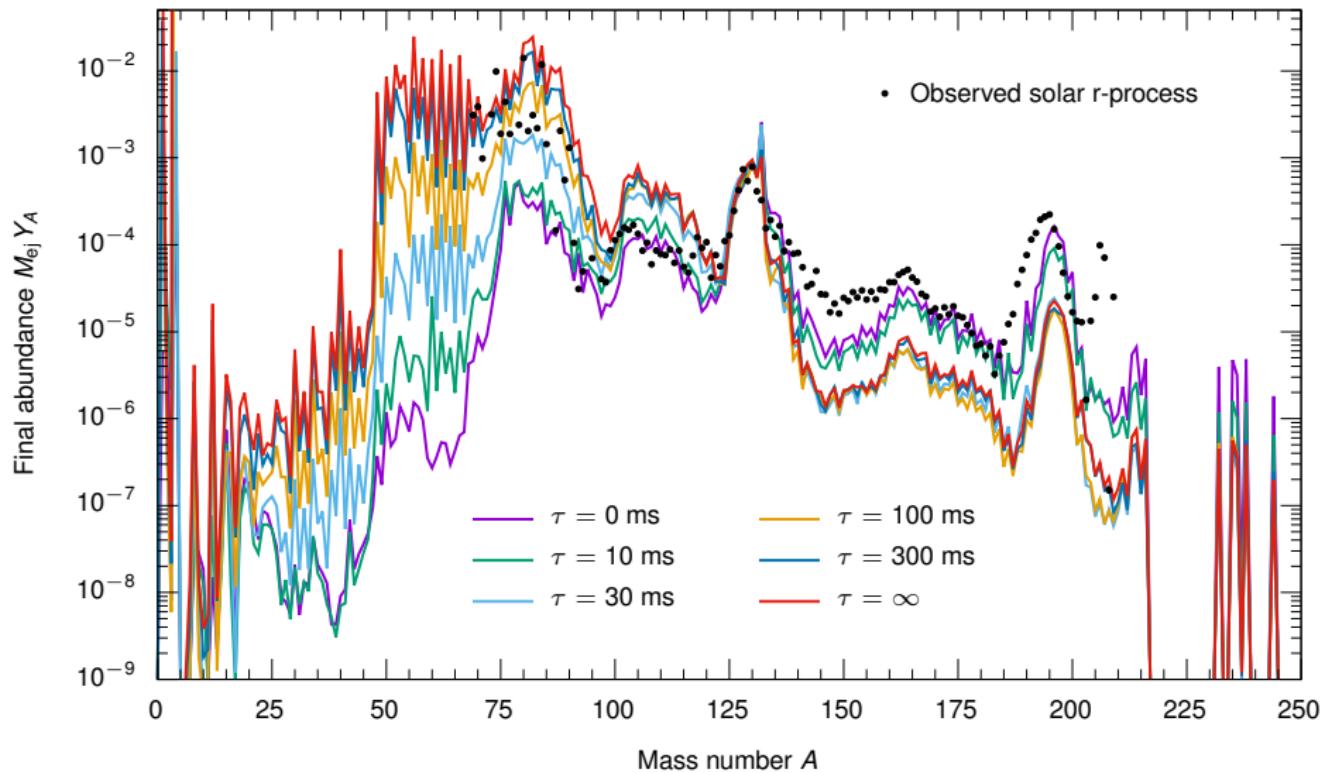


Figure from Metzger & Fernández (2014)

Final abundances



JL, Fernández, Roberts, et al. 2017, MNRAS 472, 904, arXiv:1703.06216

Black hole–neutron star merger

Roberts, JL, Duez, et al. 2017, *MNRAS* 464, 3907, arXiv:1601.07942

1. Full GR simulation of BH–NS
Francois Foucart (UNH), *Foucart et al.*,
Phys. Rev. D 90, 024026 (2014)
2. Evolve ejecta in SPH code
Matt Duez (WSU)
3. Nucleosynthesis with varying neutrino luminosity
JL and Luke Roberts (MSU)

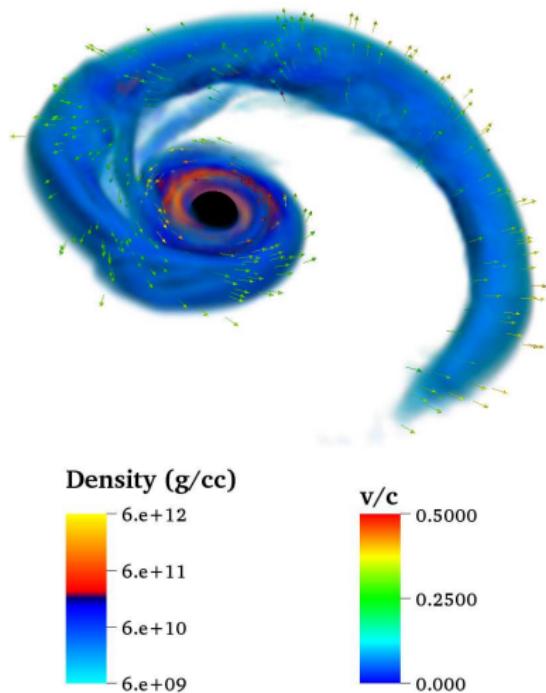
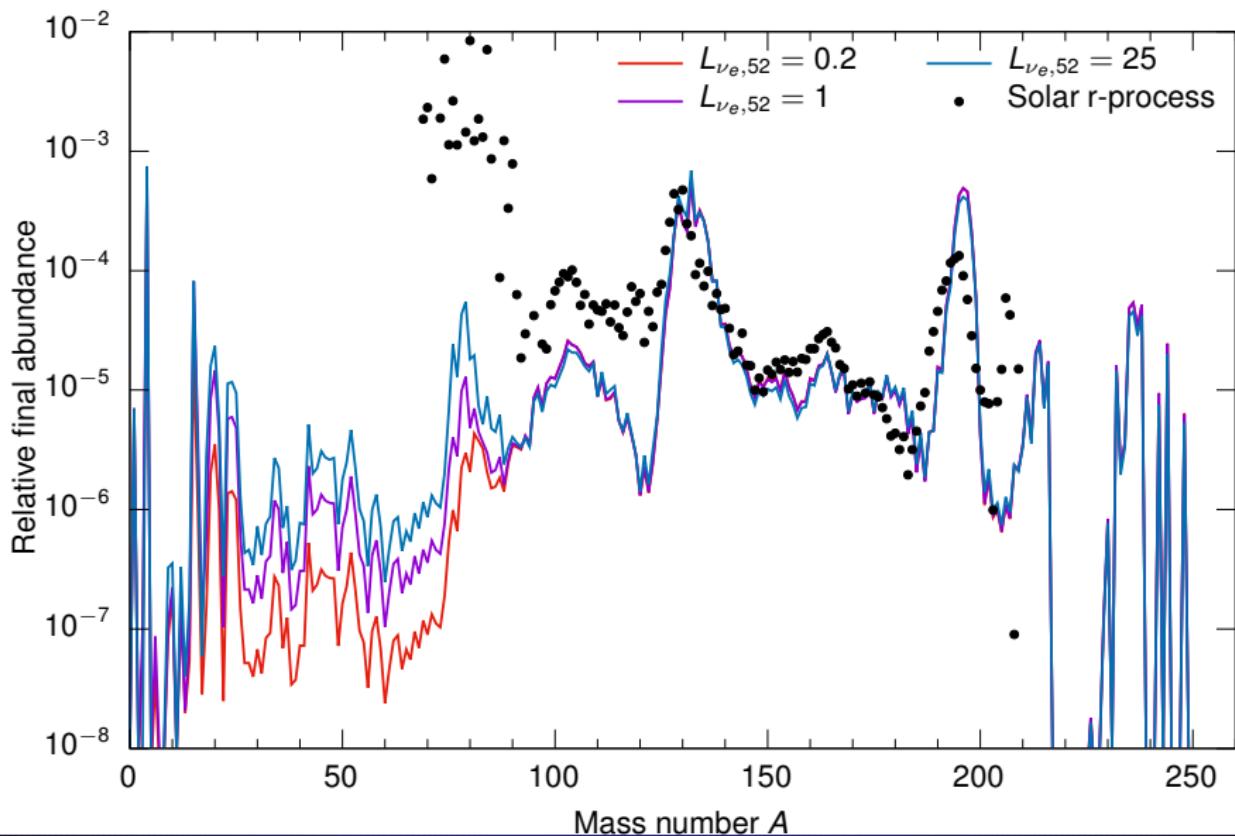


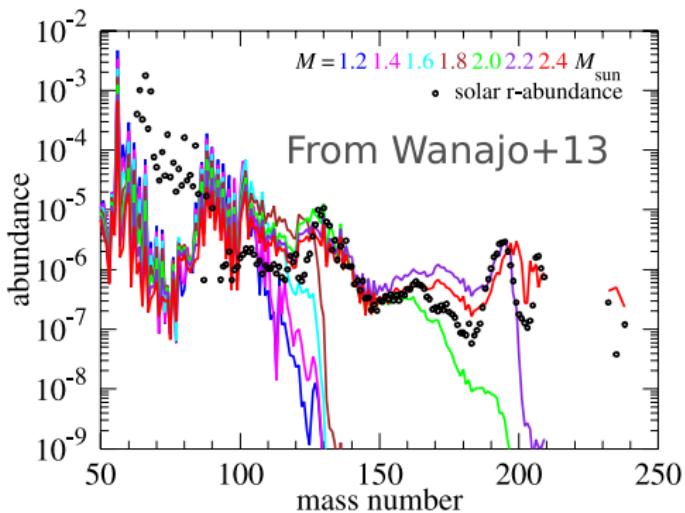
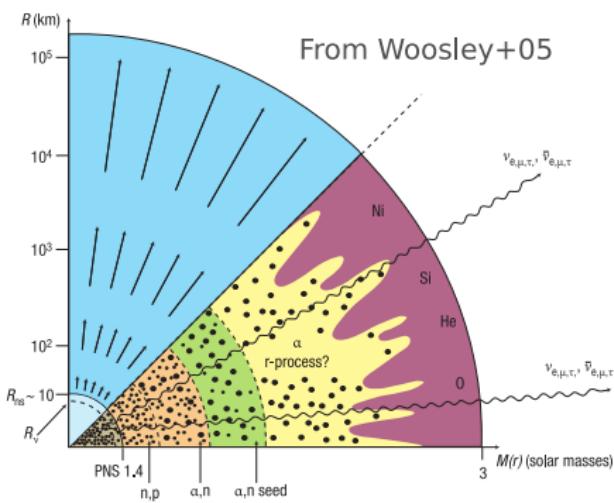
Figure credit: F. Foucart

BHNS: Final abundances vs. neutrino luminosity



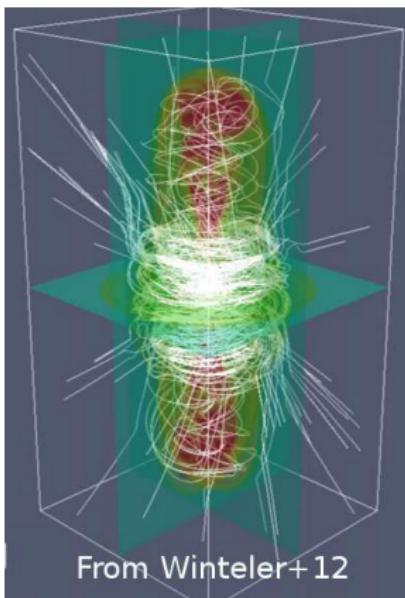
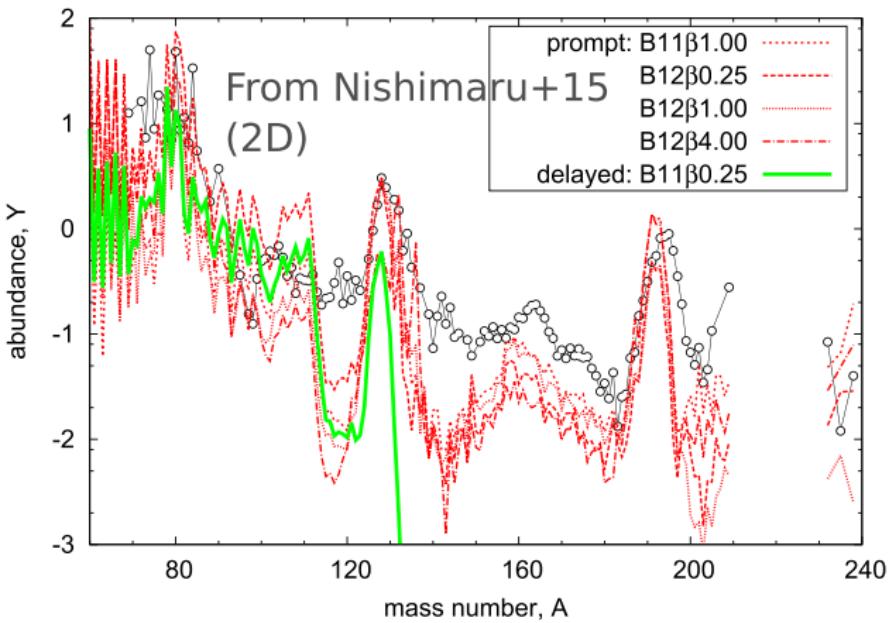
Neutrino driven wind in core-collapse supernovae

- Neutrinos emitted from hot proto-neutron star can drive outflow of n and p
- Neutrino driven wind is mildly neutron-rich → r-process?

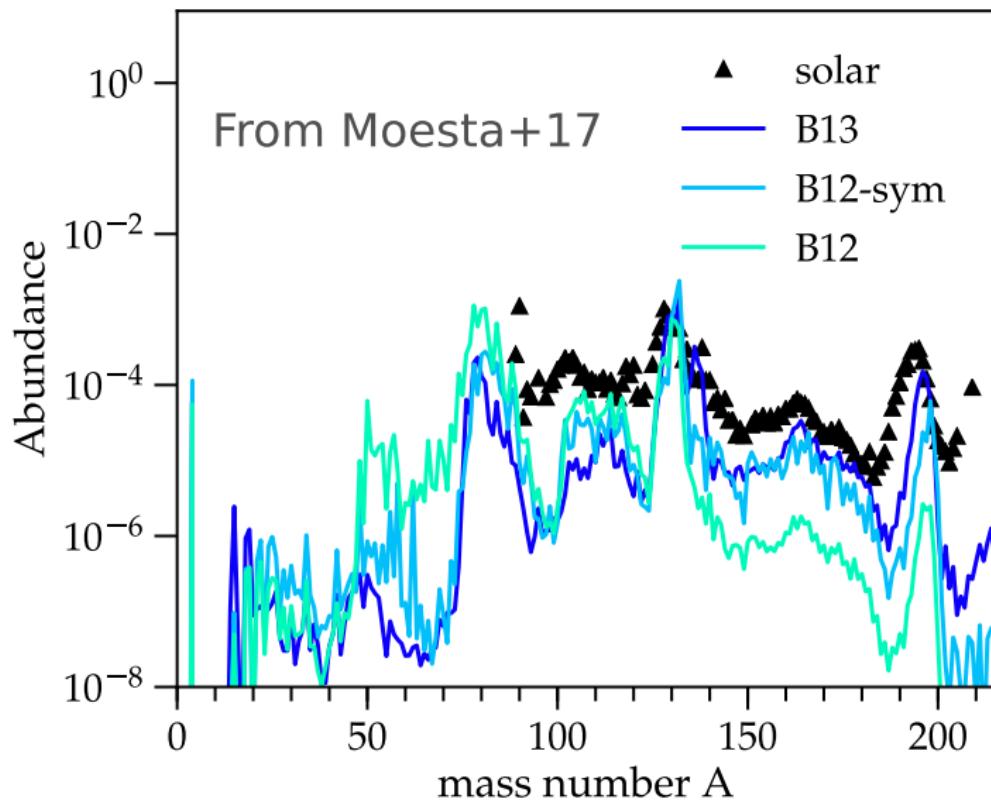


Jet in MHD-driven supernova

- Requires very high magnetic field ($B \sim 10^{12} - 10^{13}$ G) and rapid rotation
- Maybe 0.1 – 1% of all core-collapse supernovae



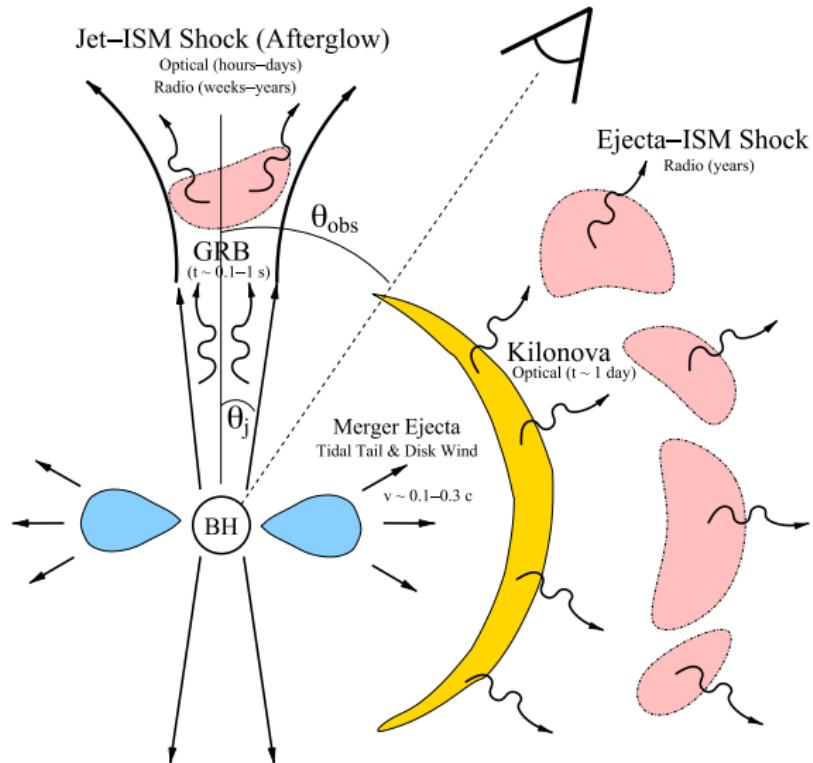
Jet in MHD-driven supernova



Outline

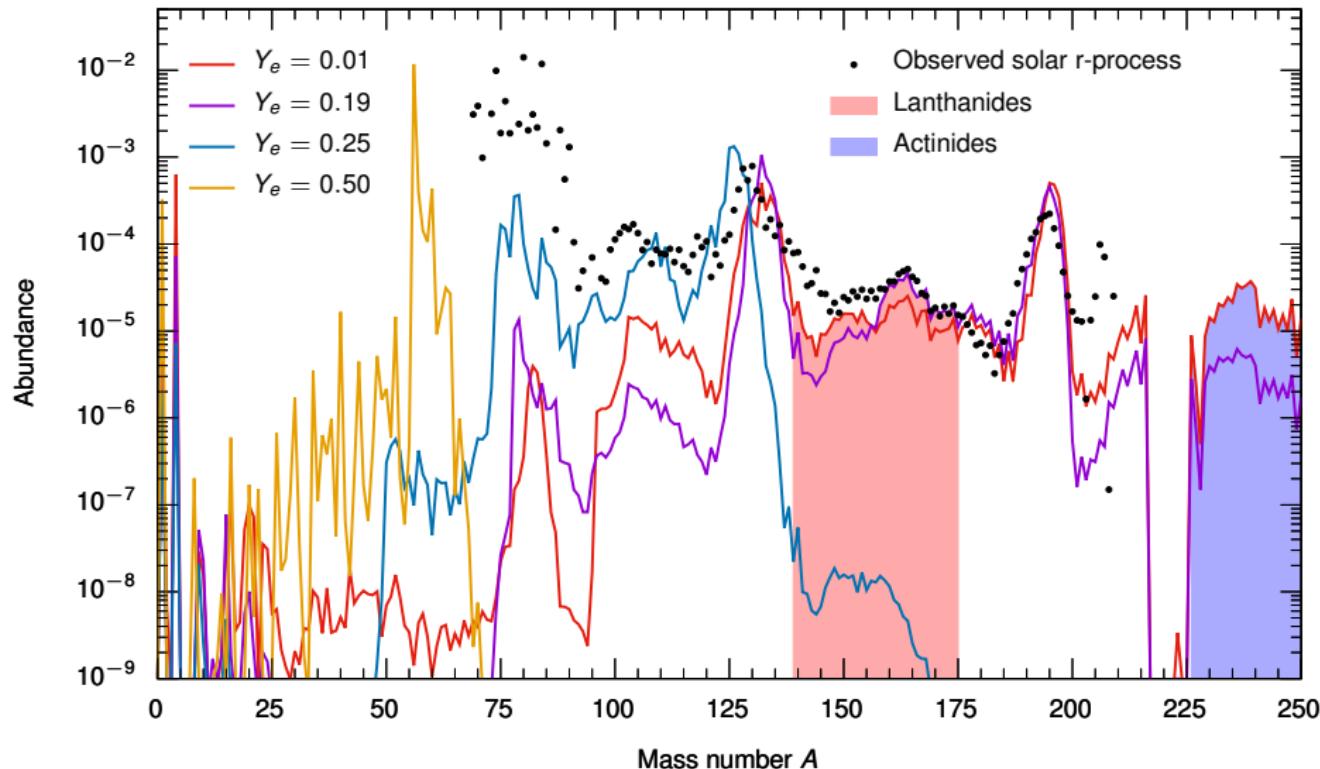
1. r-Process nucleosynthesis overview
2. r-Process in neutron star mergers
3. **Observational signature and first detection**

Observational signature of r-process: Kilonova

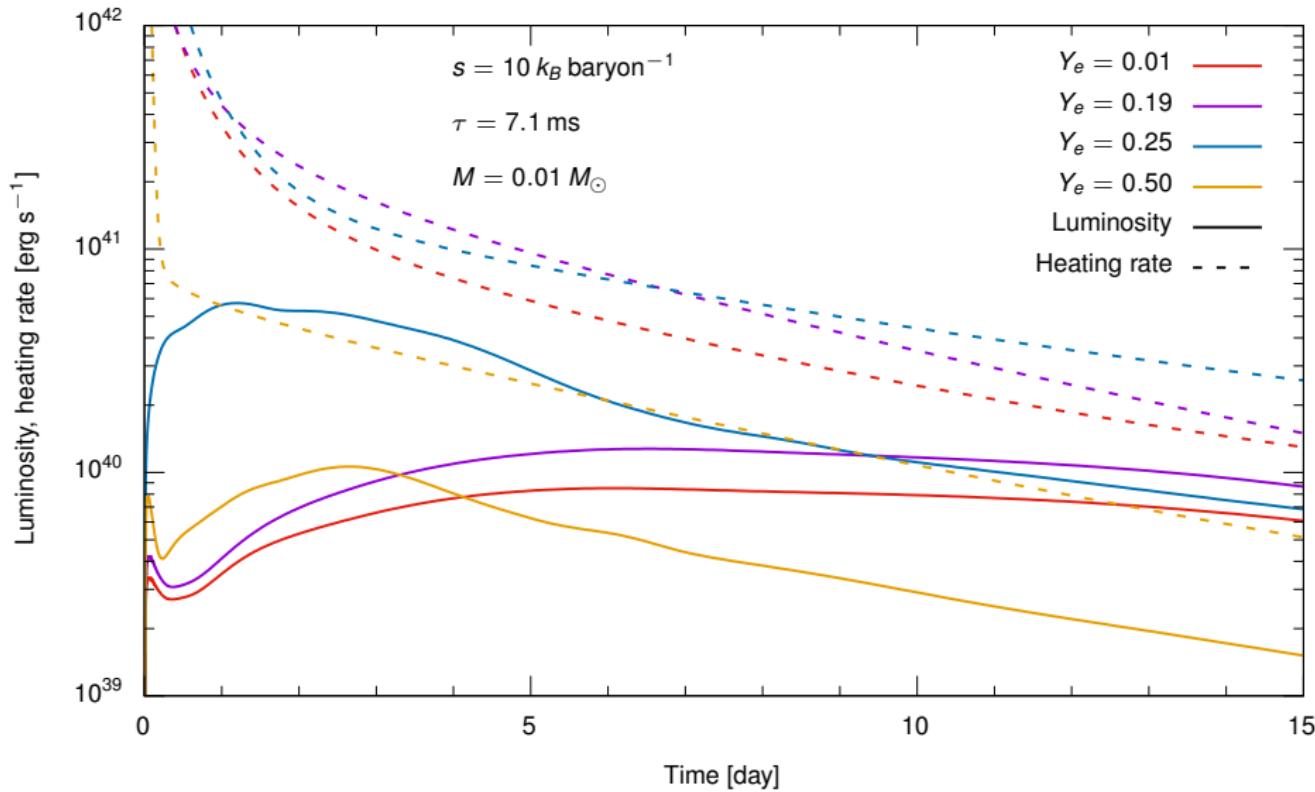


Metzger & Berger, 2012, ApJ 746, 48

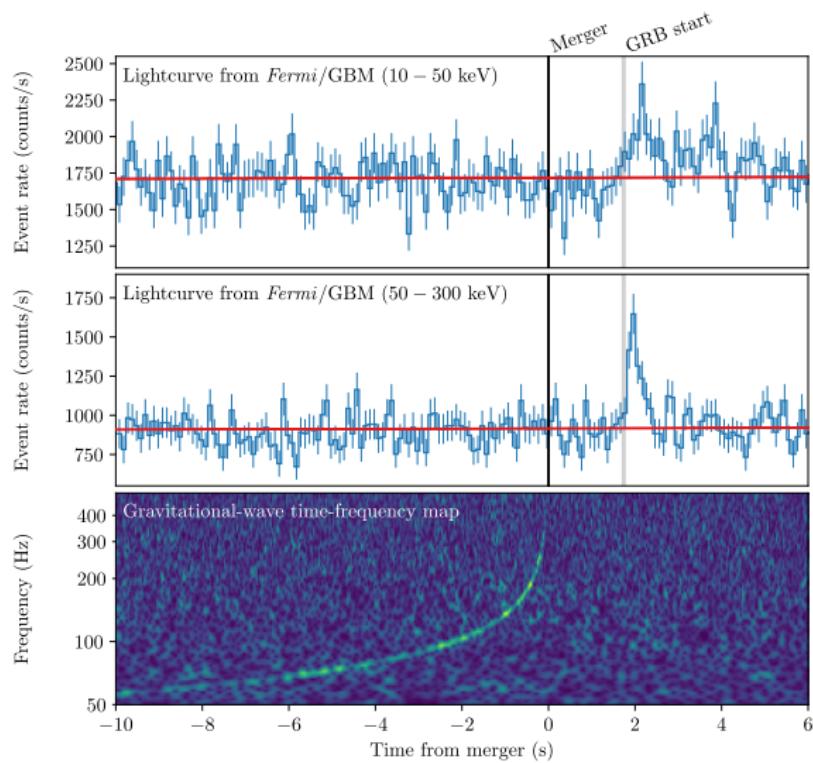
Impact of lanthanides



Impact of lanthanides



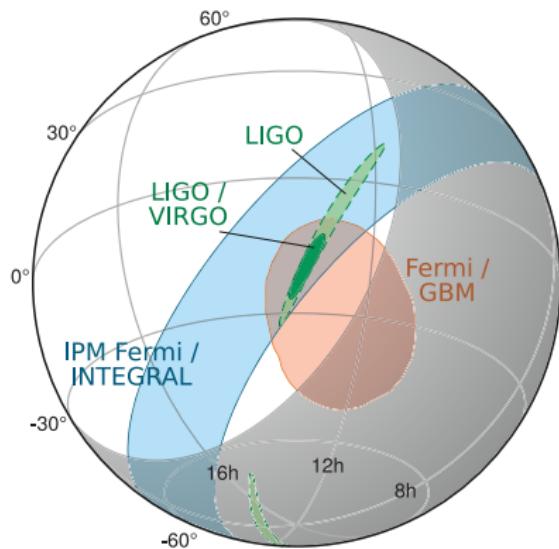
First neutron star merger observation: GW170817



LIGO et al. 2017, ApJL 848, L13

GW170817: Hunt for electromagnetic counterpart

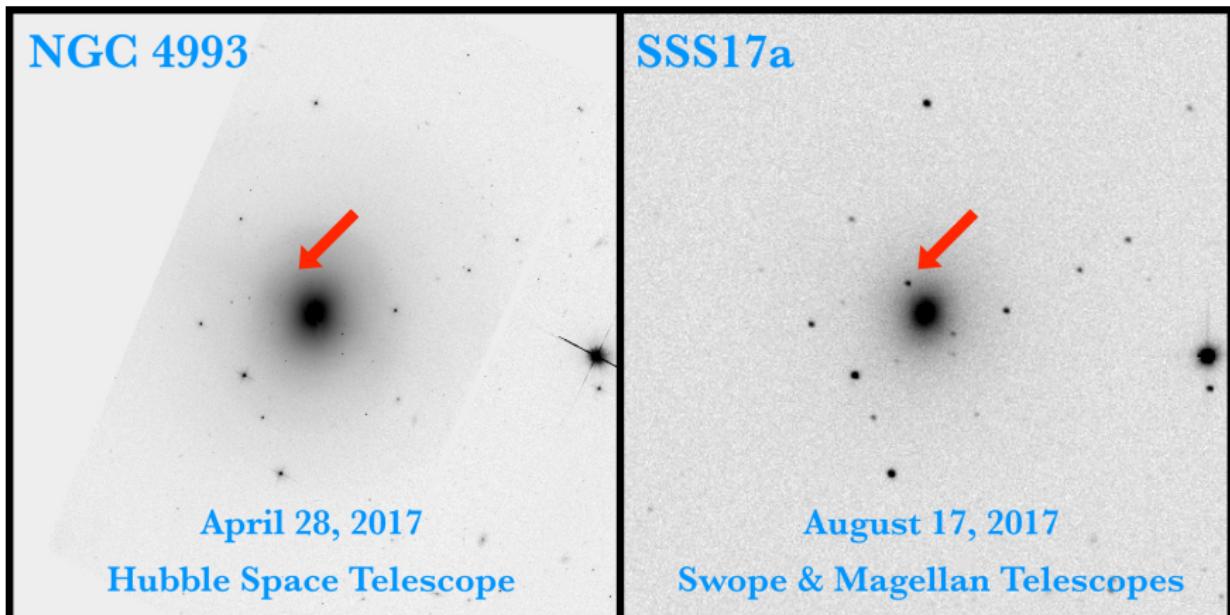
- LIGO/VIRGO localization: 31 deg^2
 ~ 150 full moons
- Distance estimate: $40 \pm 8 \text{ Mpc}$
- 49 galaxies in that volume
- Check all galaxies starting with most massive first



Kasliwal et al., 2017, Science 358, 1559

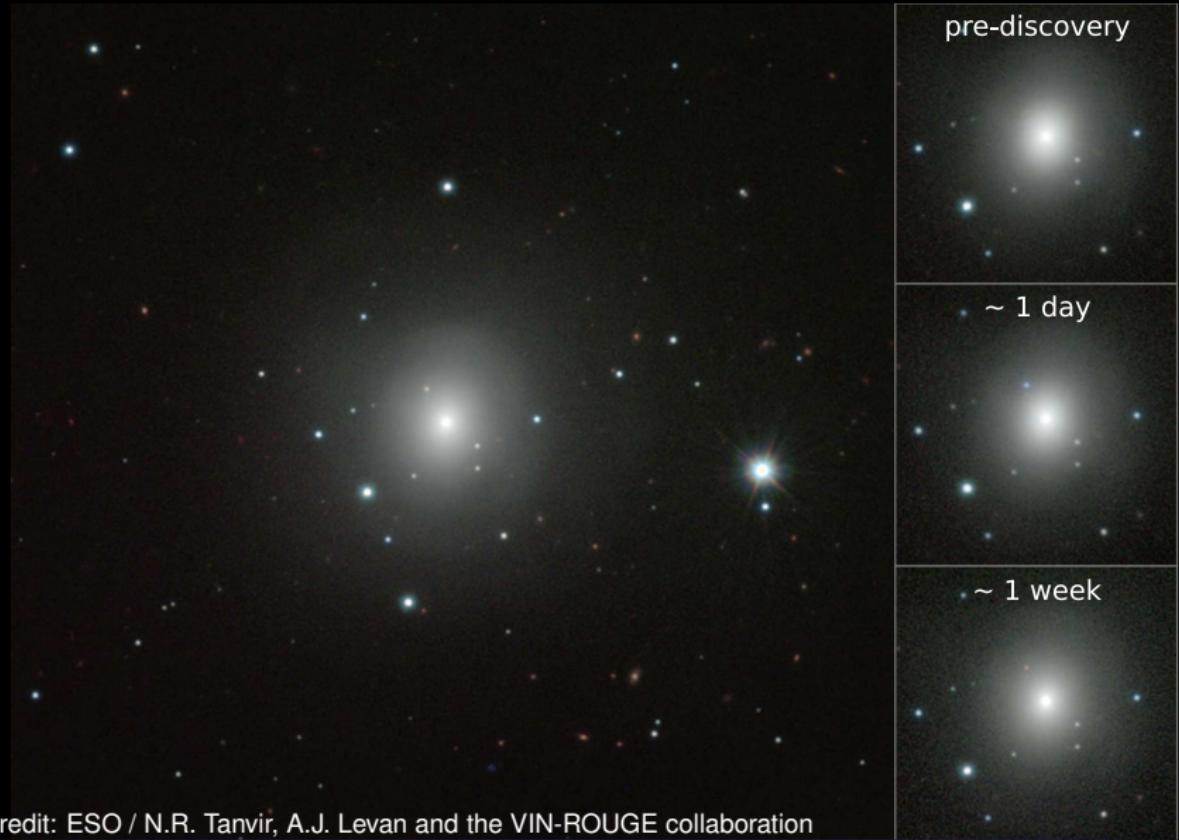
GW170817: Counterpart discovered in NGC 4993

- Discovered 10.9 hours after merger
- Host galaxy: NGC 4993, elliptical galaxy, constellation Hydra, 40 Mpc
~ 130 Mly



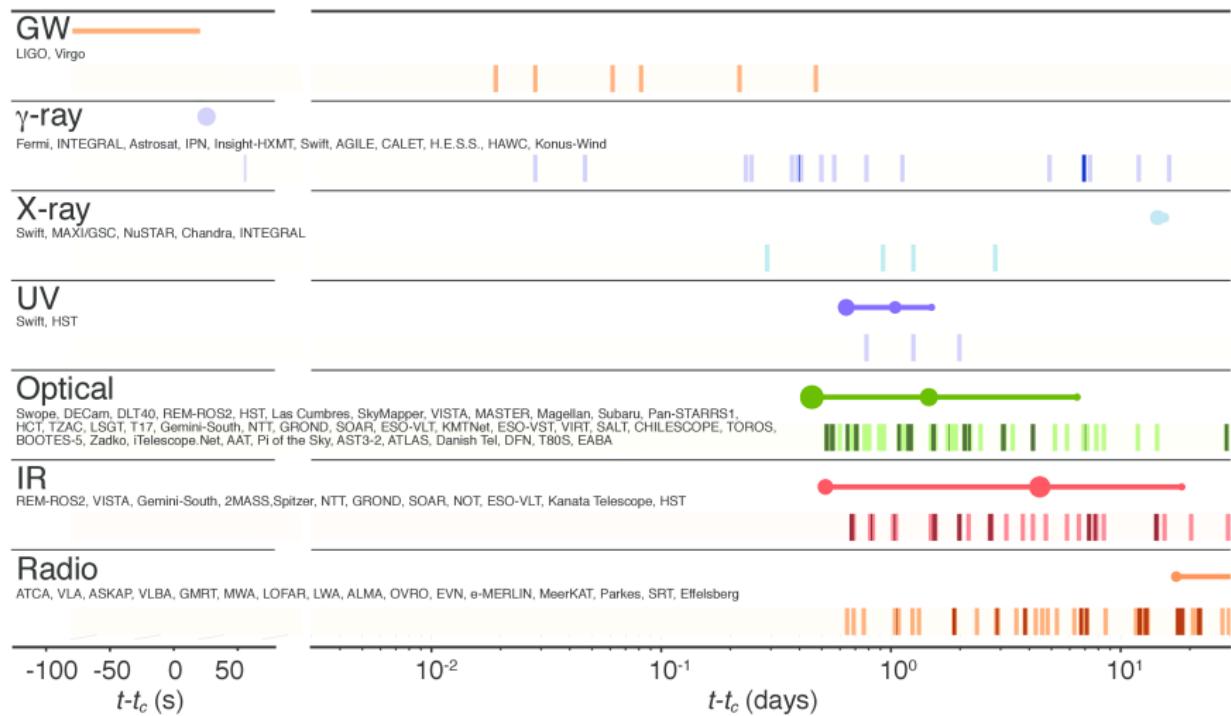
Credit: 1M2H Team / UC Santa Cruz & Carnegie Observatories / Ryan Foley

GW170817: Rapid color evolution



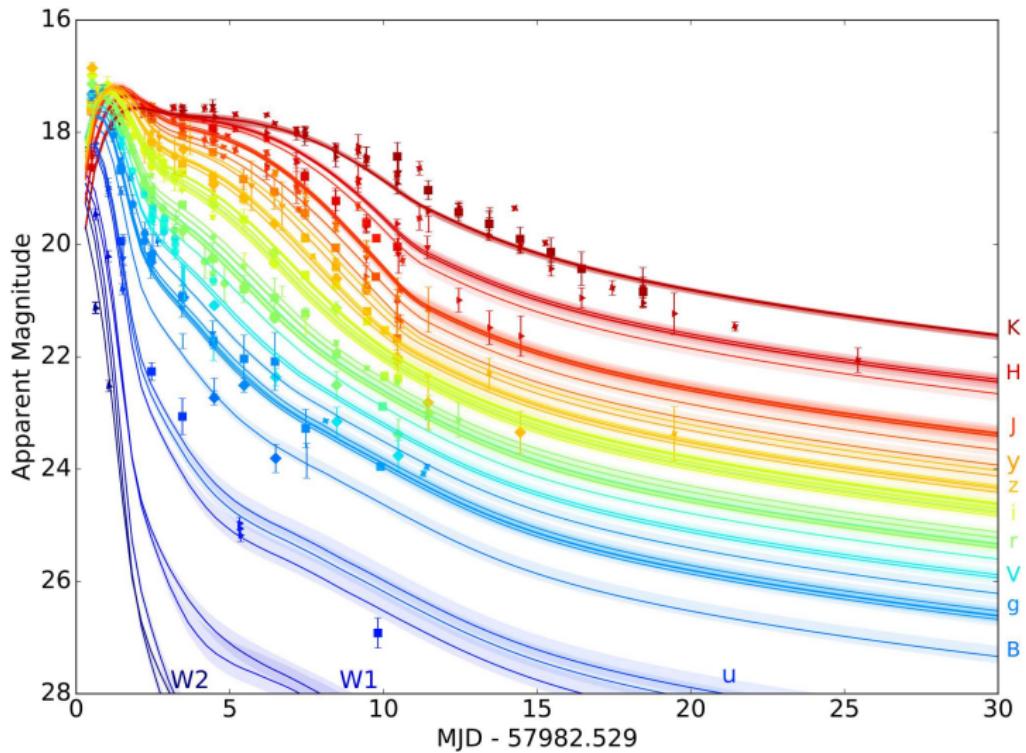
Credit: ESO / N.R. Tanvir, A.J. Levan and the VIN-ROUGE collaboration

GW170817: Huge observing campaign



LIGO et al., 2017, ApJL 848, L12

GW170817: Combined light curve

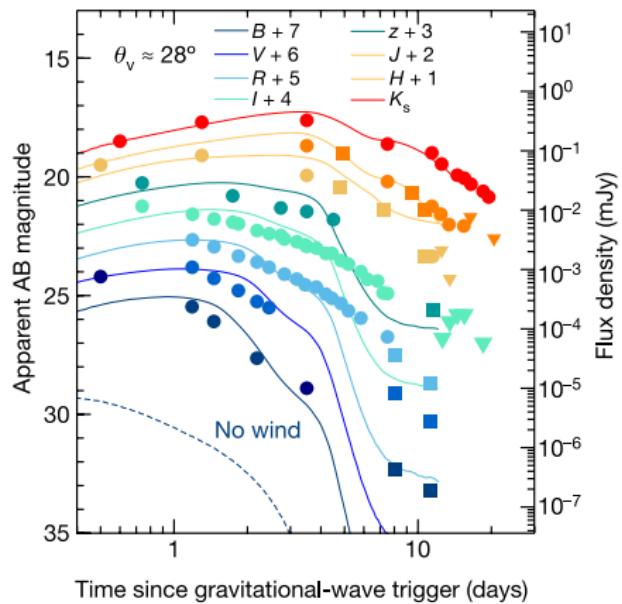


Villar et al., 2017, ApJL 851, L21

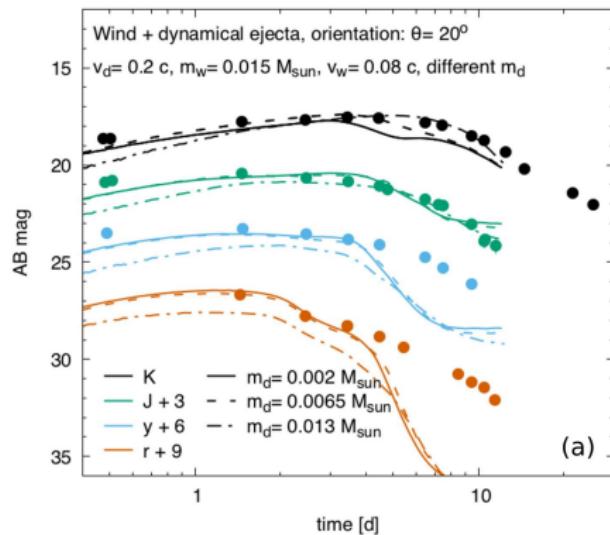
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GW170817: Two-component models do better

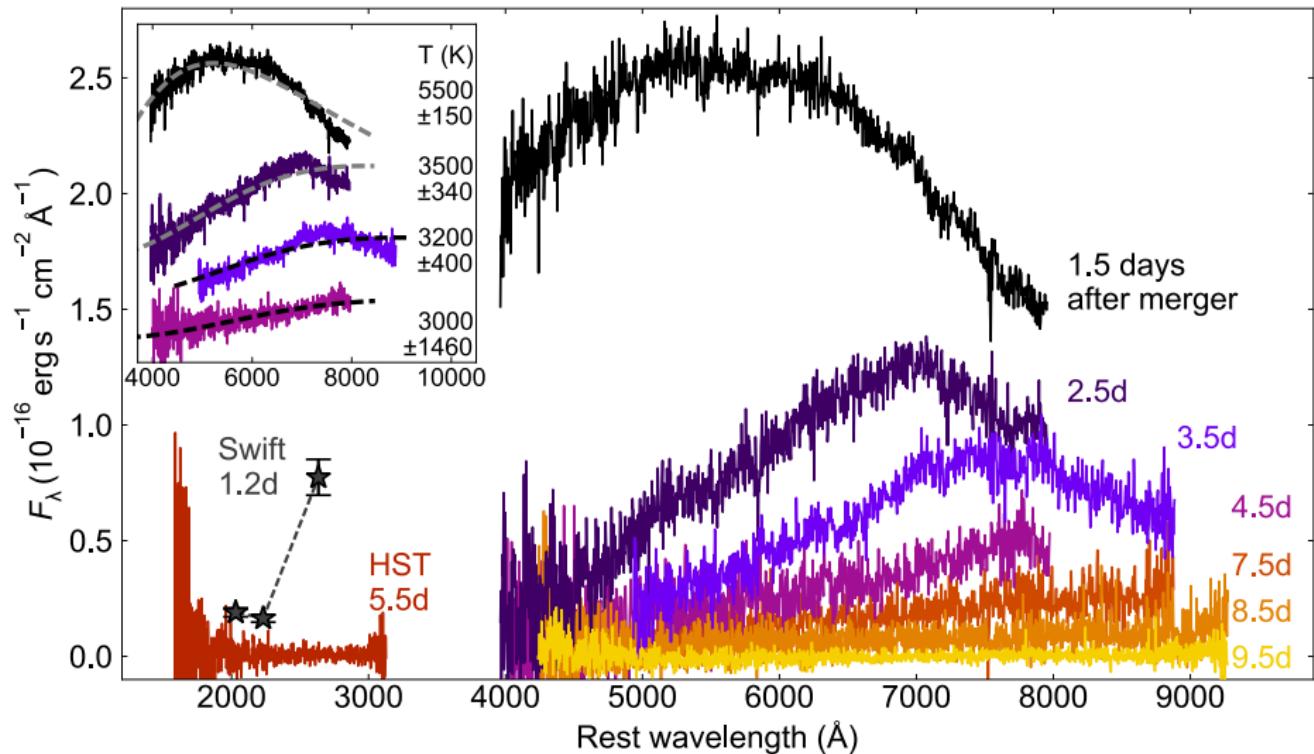


Troja et al., 2017, Nature 551, 71



Tanvir et al., 2017, ApJL 848, L27

GW170817: Featureless optical spectrum



Nicholl et al., 2017, ApJL 848, L18

GW170817: What we learned

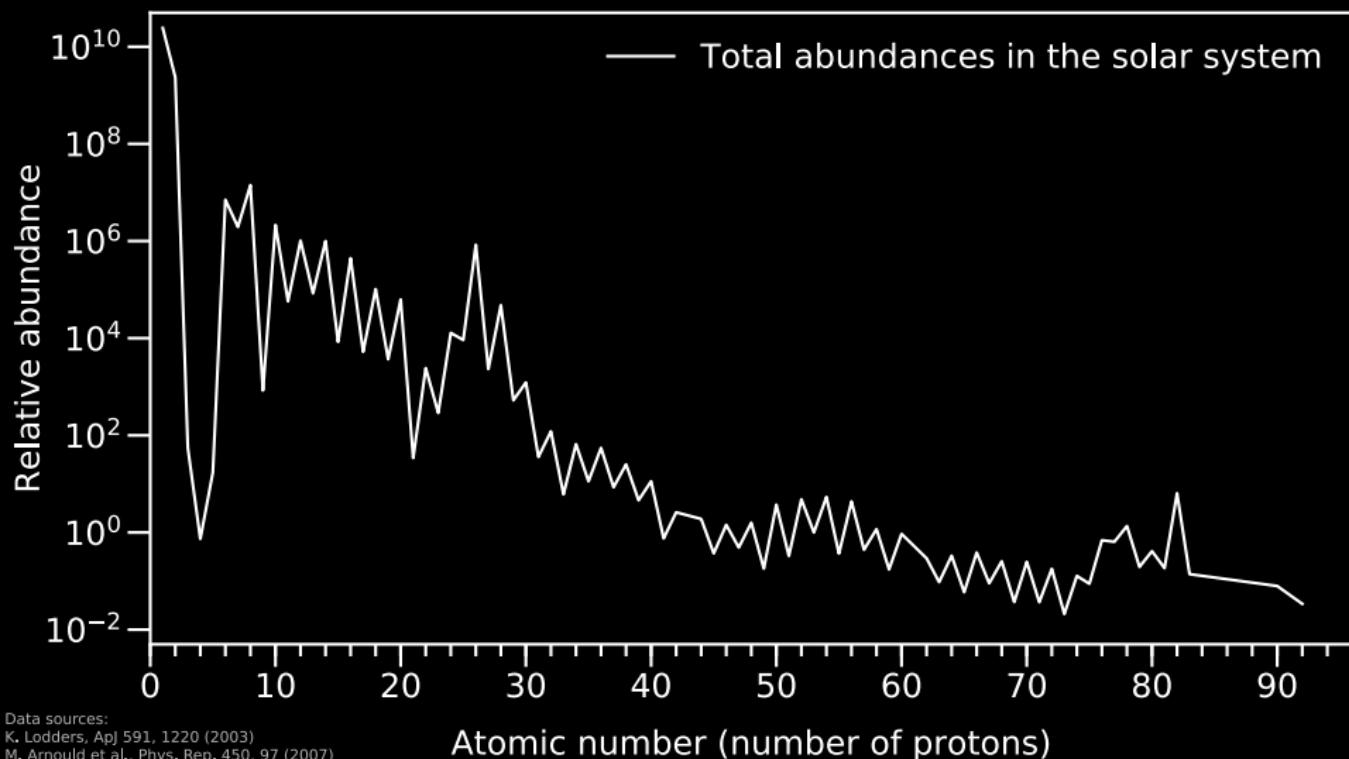
- Confirmed neutron star mergers make short GRBs
- Total ejecta mass larger than expected: $\sim 5 \times 10^{-2} M_{\odot}$ (may strongly depend on light curve model)
- Neutron star mergers can easily make all r-process material in the galaxy
- Blue (lanthanide-free) component larger than expected, maybe large disk wind or blue dynamical component
- Lanthanide-rich component is evidence for full r-process, tens of Earth masses of gold and platinum
- Gravity propagates at the speed of light, rules out many alternative theories of gravity besides Einstein's General Relativity

Summary

- s- and r-process create heavy elements beyond the iron peak
- r-process happens in dynamical and disk ejecta in a neutron star merger
- Dynamical ejecta (NS-NS and BH-NS) is generally neutron-rich enough for full r-process
- Neutron star mergers are probably the dominant site of the r-process, core-collapse supernovae may contribute weakly
- GW170817: First LIGO detection of neutron star merger accompanied by GRB and kilonova
 - Kilonova followed pretty well what we expected
 - Much more work is needed to understand light curve in detail
 - Expecting many more observations in the near future

Extra slides

Solar system abundances



Data sources:
K. Lodders, ApJ 591, 1220 (2003)
M. Arnould et al., Phys. Rep. 450, 97 (2007)

First (wrong) attempt: $\alpha\beta\gamma$

PHYSICAL REVIEW

VOLUME 73, NUMBER 7

APRIL 1, 1948

Letters to the Editor

PUBLICATION of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is five weeks prior to the date of issue. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length.

The Origin of Chemical Elements

R. A. ALPHER*

Applied Physics Laboratory, The Johns Hopkins University,
Silver Spring, Maryland

AND

H. BETHE

Cornell University, Ithaca, New York

AND

G. GAMOW

The George Washington University, Washington, D. C.
February 18, 1948

A S pointed out by one of us,¹ various nuclear species must have originated not as the result of an equilibrium corresponding to a certain temperature and density, but rather as a consequence of a continuous building-up process arrested by a rapid expansion and cooling of the primordial matter. According to this picture, we must imagine the early stage of matter as a highly compressed neutron gas (overheated neutral nuclear fluid) which

We may remark at first that the building-up process was apparently completed when the temperature of the neutron gas was still rather high, since otherwise the observed abundances would have been strongly affected by the resonances in the region of the slow neutrons. According to Hughes,² the neutron capture cross sections of various elements (for neutron energies of about 1 Mev) increase exponentially with atomic number halfway up the periodic system, remaining approximately constant for heavier elements.

Using these cross sections, one finds by integrating Eqs. (1) as shown in Fig. 1 that the relative abundances of various nuclear species decrease rapidly for the lighter elements and remain approximately constant for the elements heavier than silver. In order to fit the calculated curve with the observed abundances³ it is necessary to assume the integral of ρ_ndt during the building-up period is equal to 5×10^4 g sec./cm.³

On the other hand, according to the relativistic theory of the expanding universe⁴ the density dependence on time is given by $\rho \cong 10^4/t^2$. Since the integral of this expression diverges at $t = 0$, it is necessary to assume that the building-up process began at a certain time t_0 , satisfying the relation:

$$\int_{t_0}^{\infty} (10^4/t^2) dt \cong 5 \times 10^4, \quad (2)$$

which gives us $t_0 \cong 20$ sec. and $\rho_0 \cong 2.5 \times 10^6$ g sec./cm.³ This result may have two meanings: (a) for the higher densities existing prior to that time the temperature of the neutron gas was so high that no aggregation was taking place, (b) the density of the universe never exceeded the value

Birth of modern theory of nucleosynthesis: B²FH

REVIEWS OF MODERN PHYSICS

VOLUME 29, NUMBER 4

OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

*Kellogg Radiation Laboratory, California Institute of Technology, and
Mount Wilson and Palomar Observatories, Carnegie Institution of Washington,
California Institute of Technology, Pasadena, California*

"It is the stars, The stars above us, govern our conditions";

(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"

(*Julius Caesar*, Act I, Scene 2)

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A. Element Abundances and Nuclear Structure.....	549

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Define abundance

$$Y_i = \frac{n_i}{n_B}. \quad (1)$$

Consider reaction



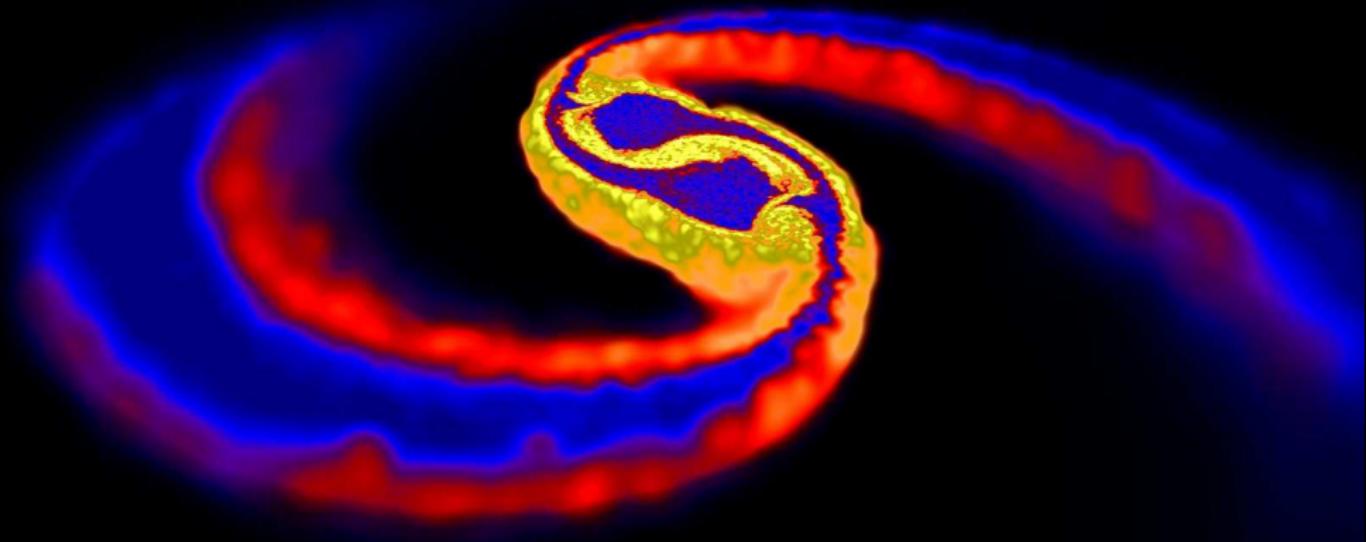
with rate $\lambda = \lambda(T, \rho)$. Then

$$\begin{aligned}\dot{Y}_{{}^4\text{He}} &= 2\lambda Y_p Y_{{}^7\text{Li}} + \dots, \\ \dot{Y}_p &= -\lambda Y_p Y_{{}^7\text{Li}} + \dots, \\ \dot{Y}_{{}^7\text{Li}} &= -\lambda Y_p Y_{{}^7\text{Li}} + \dots\end{aligned} \quad (3)$$

Need to solve big, stiff, non-linear system of ODEs

NS-NS ejecta sources: Tidal tails

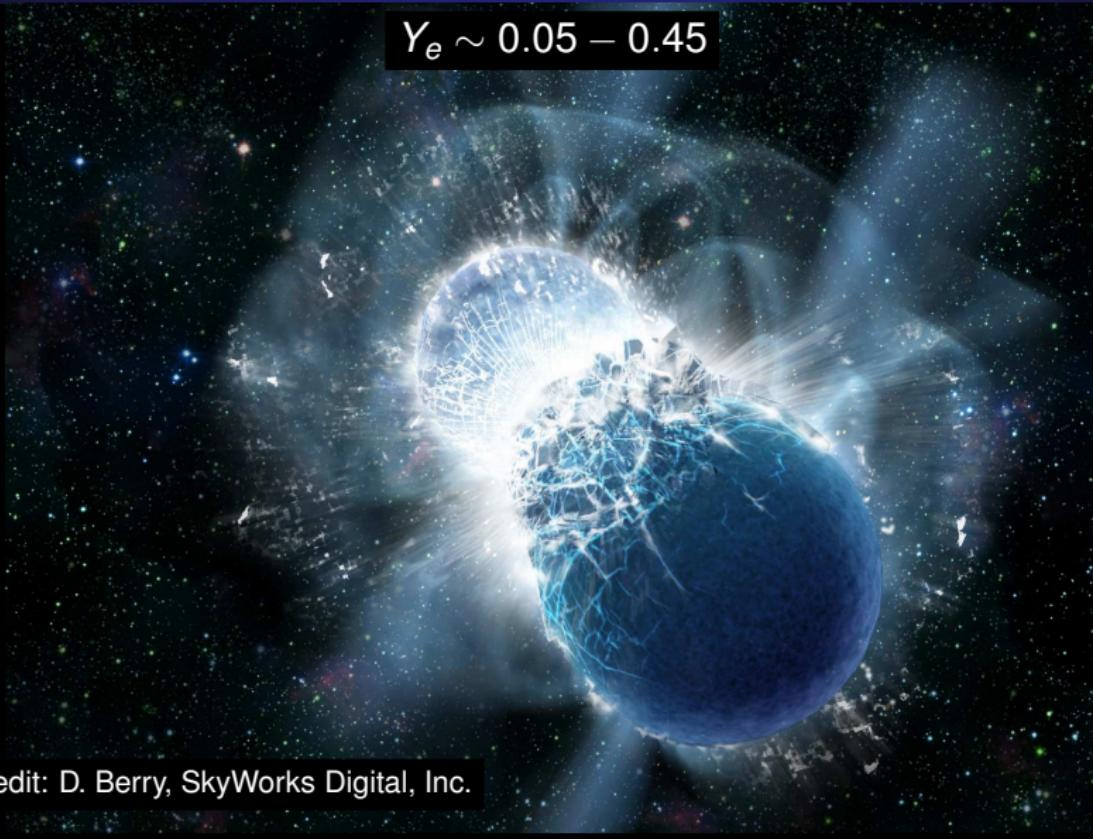
$$Y_e \sim 0.05 - 0.45$$



Credit: D. J. Price et al. (2006)

NS–NS ejecta sources: Collision interface

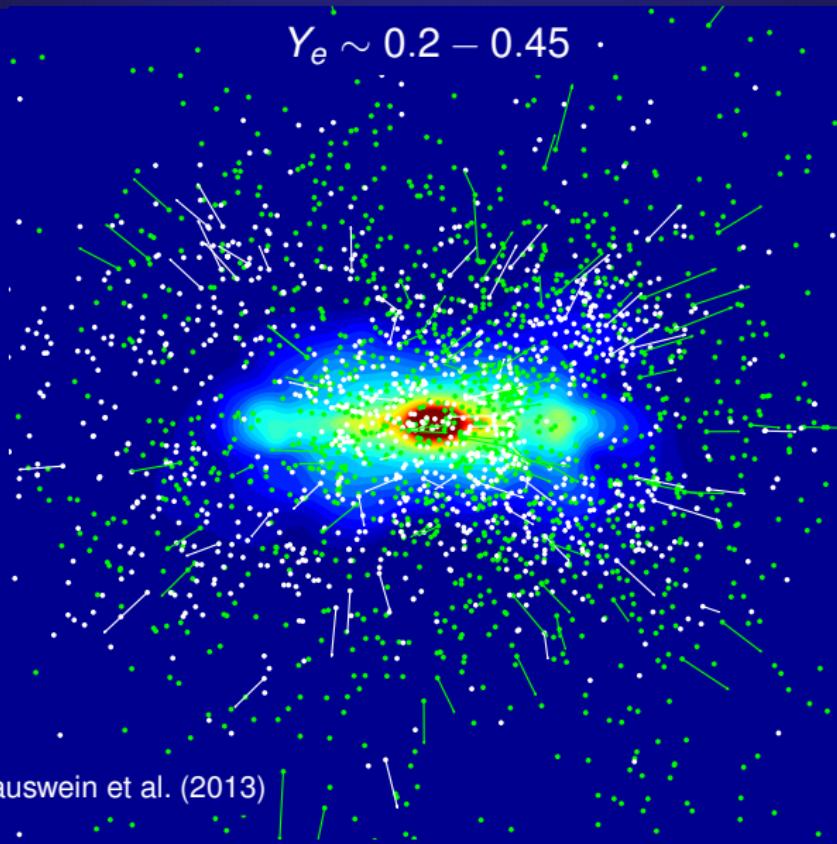
$$Y_e \sim 0.05 - 0.45$$



Credit: D. Berry, SkyWorks Digital, Inc.

NS-NS ejecta sources: Disk outflow

$$Y_e \sim 0.2 - 0.45$$



Credit: A. Bauswein et al. (2013)

Parametrized r-process

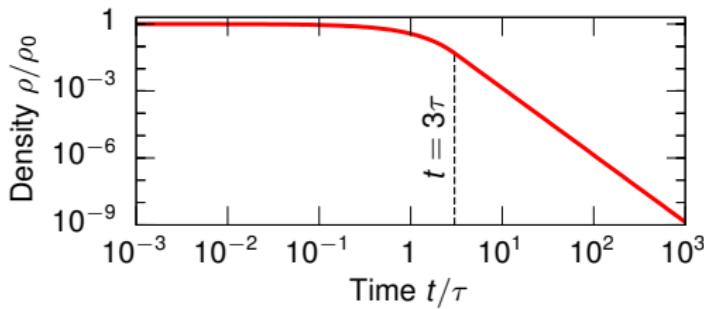
Lippuner & Roberts, 2015, ApJ, 815, 82, arXiv:1508.03133

Parameters

$$\begin{array}{ll} 0.01 \leq Y_e \leq 0.50 & \text{initial electron fraction} \\ 1 \text{ } k_B \text{ baryon}^{-1} \leq s \leq 100 \text{ } k_B \text{ baryon}^{-1} & \text{initial specific entropy} \\ 0.1 \text{ ms} \leq \tau \leq 500 \text{ ms} & \text{expansion time scale} \end{array}$$

Density profile

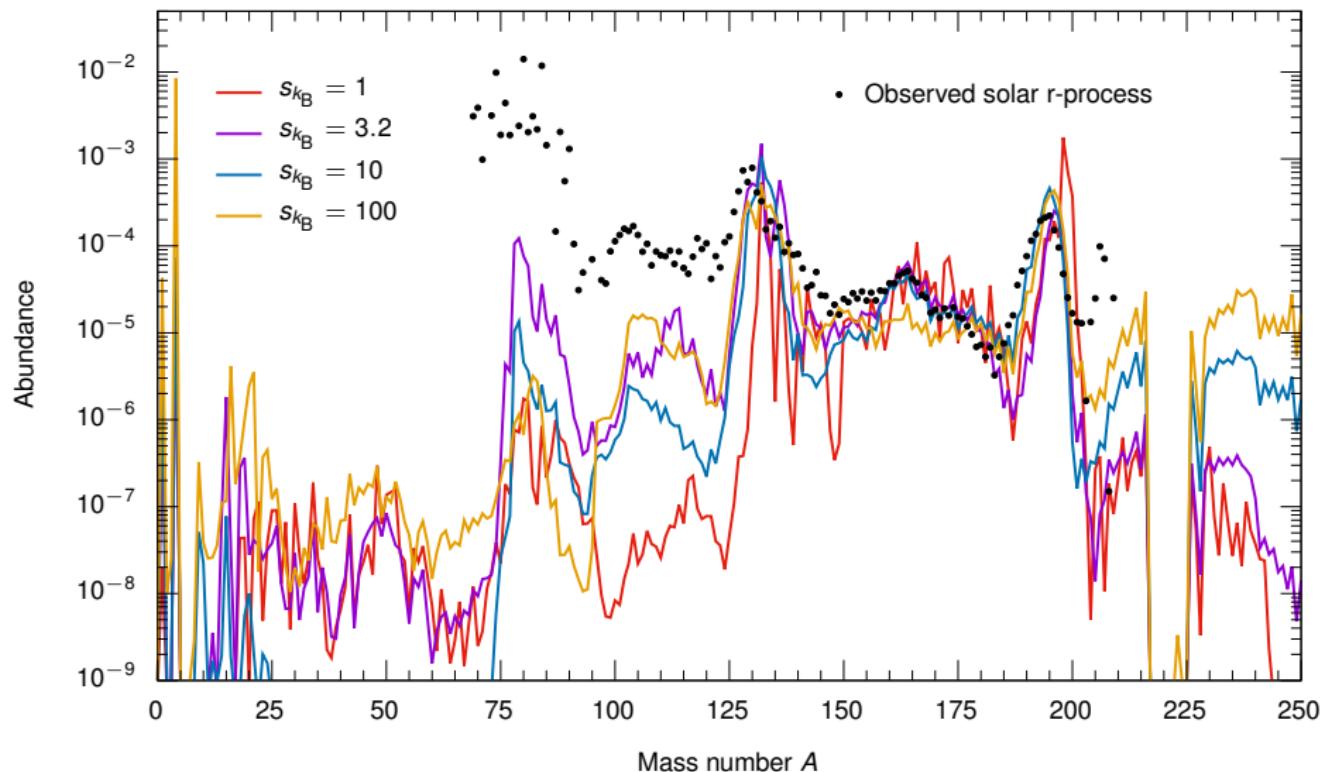
$$\rho(t, \tau) = \begin{cases} \rho_0 e^{-t/\tau} & t \leq 3\tau \\ \rho_0 \left(\frac{3\tau}{te}\right)^3 & t \geq 3\tau \end{cases}$$



Initial conditions

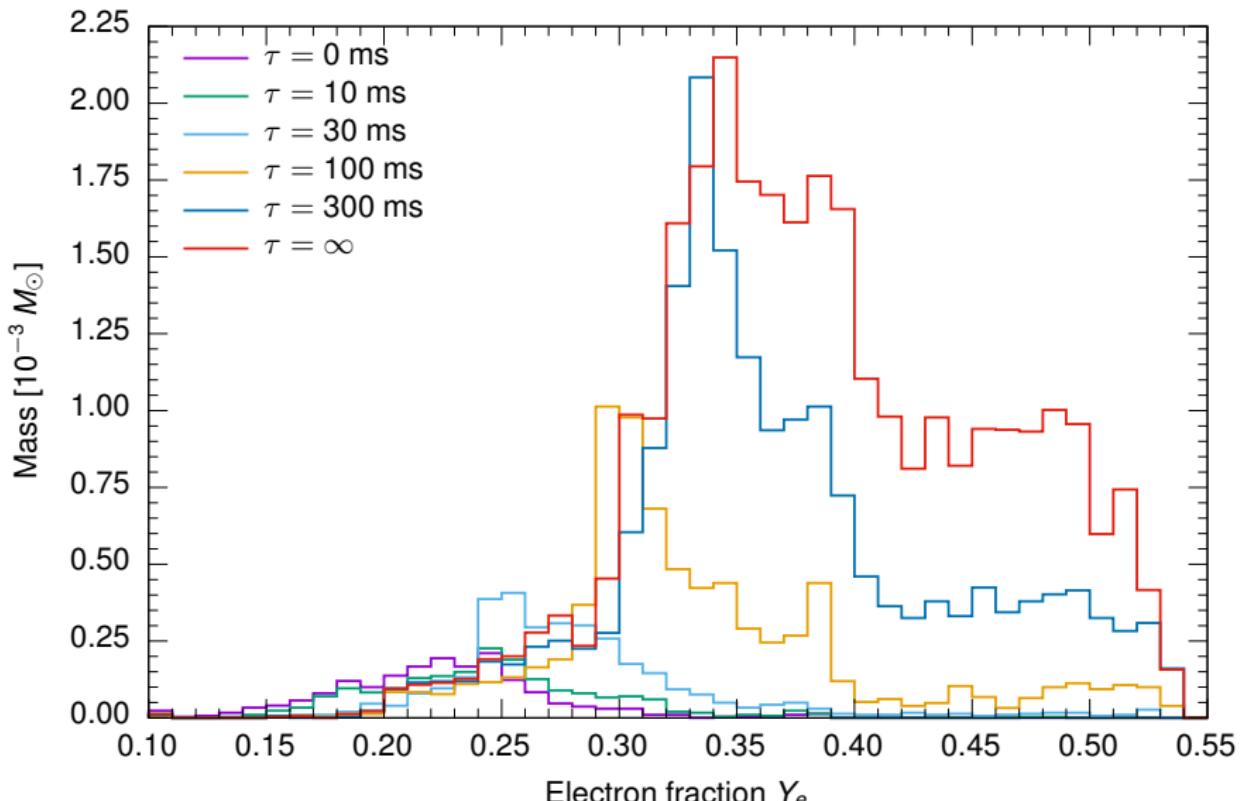
- Choose initial temperature $T_0 = 6 \text{ GK}$
- Find ρ_0 by solving for NSE at T_0 and Y_e that produces specified s

Final abundances vs. entropy

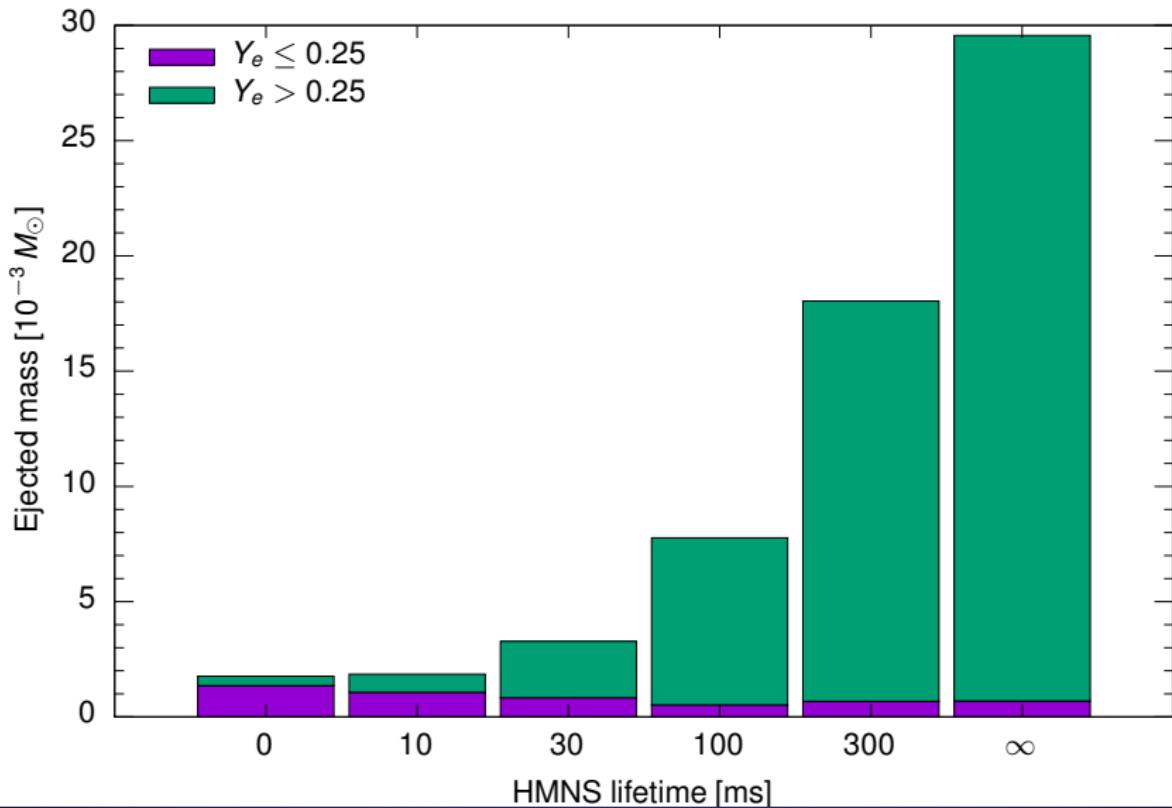


JL, Roberts 2015, ApJ 815, 82, arXiv:1508.03133

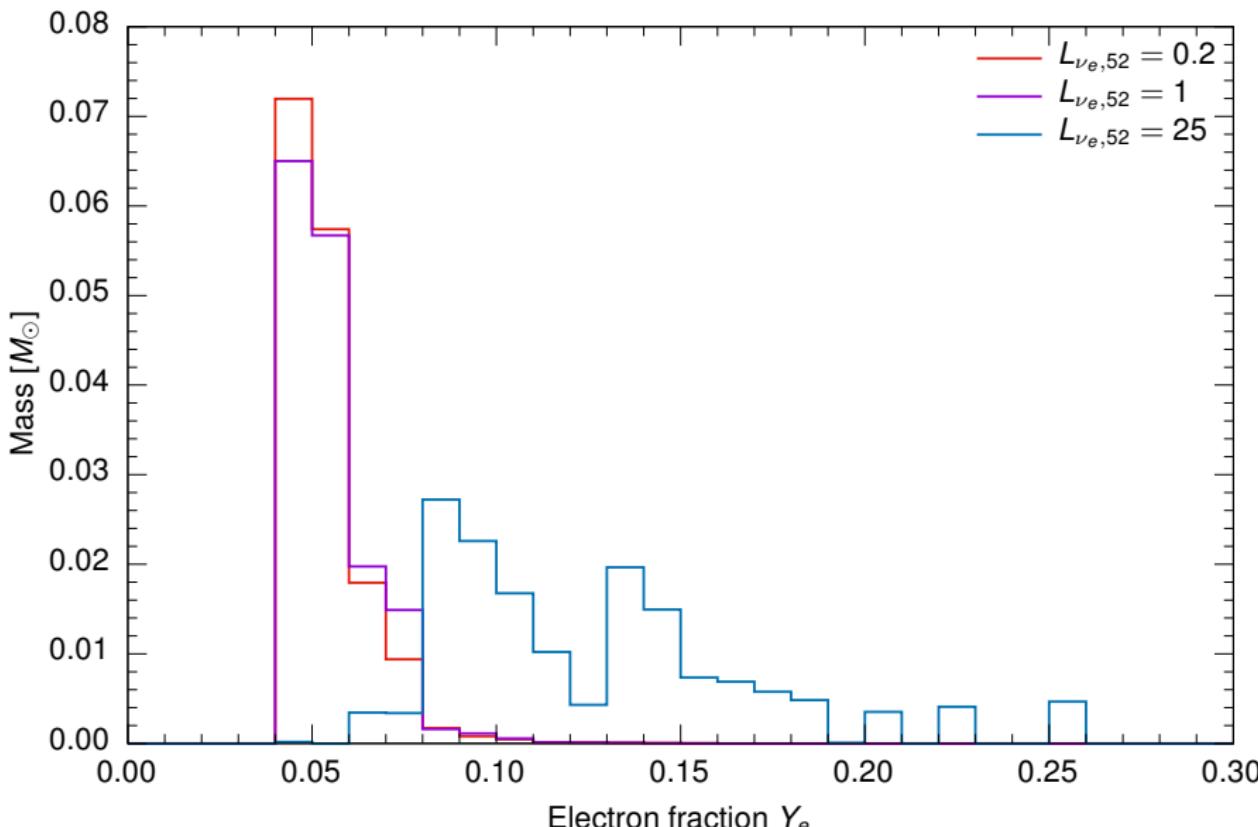
HMNS: Electron fraction distribution



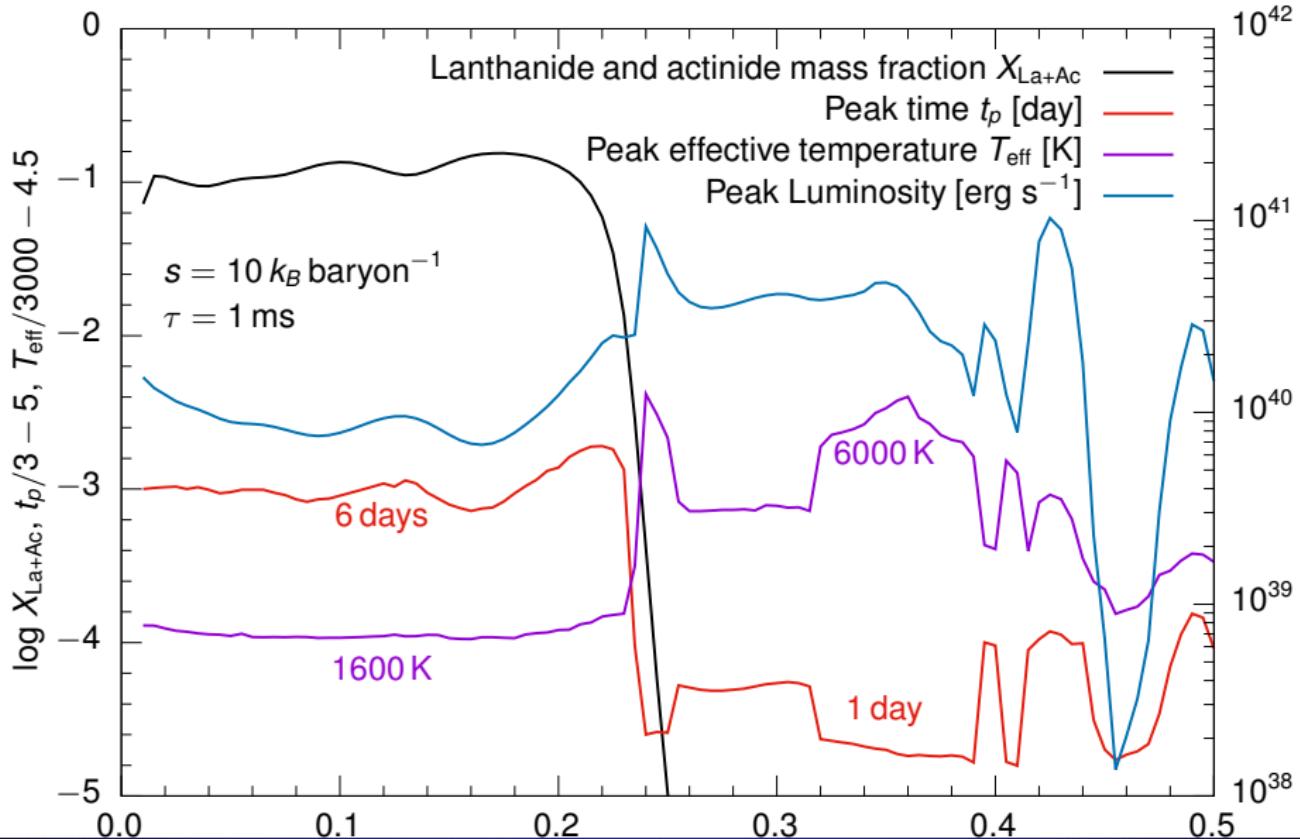
HMNS: Ejected mass



BHNS: Electron fraction distribution

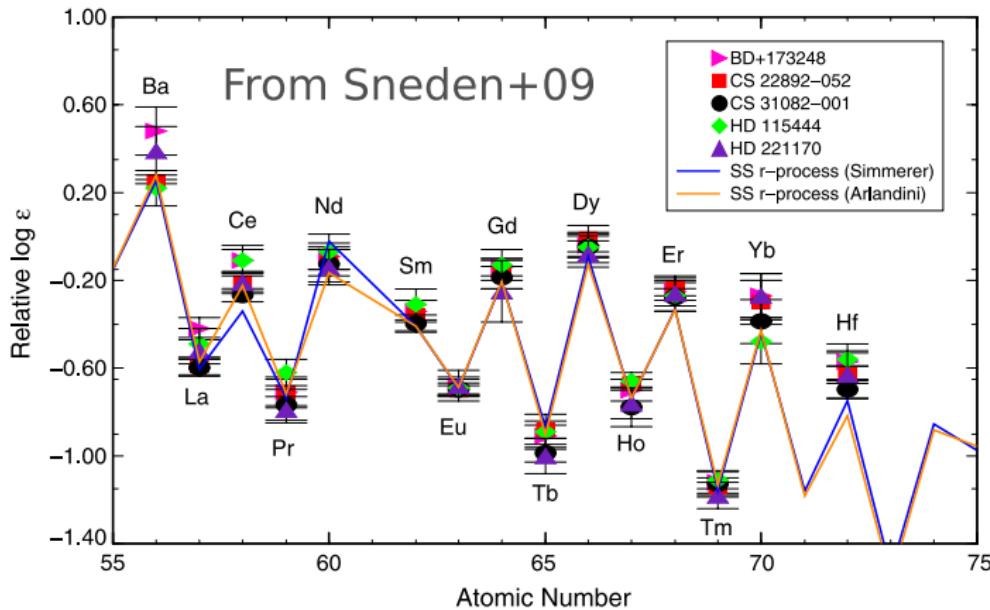


Light curves vs. electron fraction



Universal r-process pattern

- Metal-poor stars ($[\text{Fe}/\text{H}] \lesssim -2$) formed early (first few 100 Myr)
- s-process starts later as stars evolve
- Observed r-process pattern agrees with present solar system abundances
- **Conclusion:** robust and early r-process mechanism



Possible r-process sites

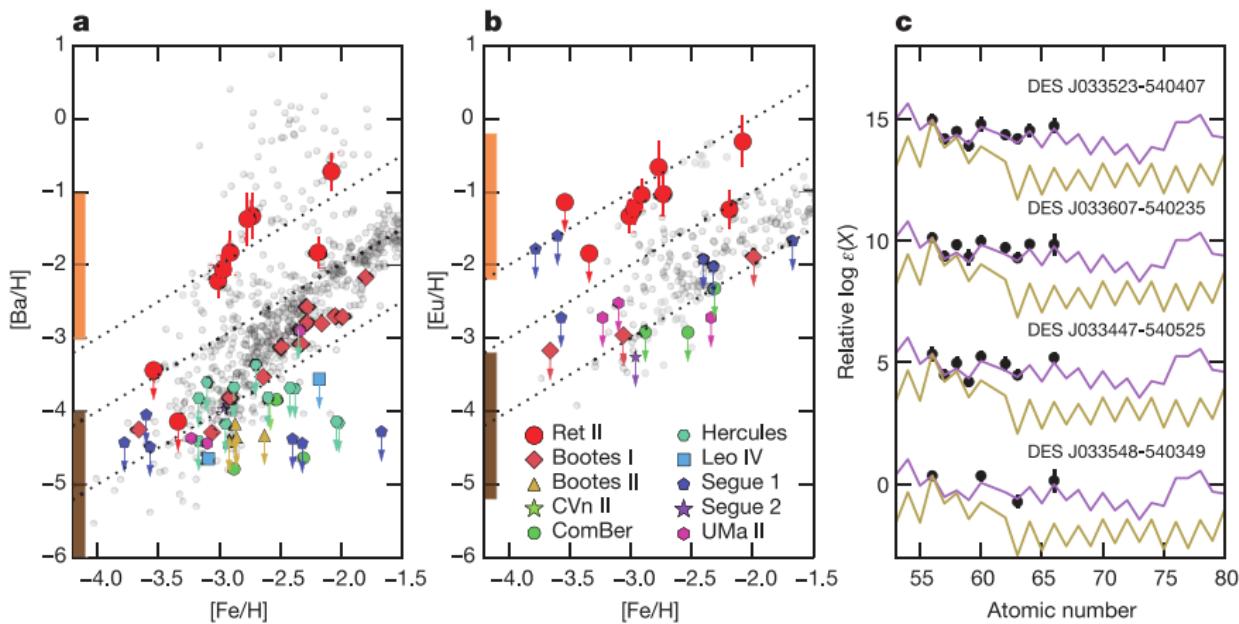
Astrophysical site of r-process nucleosynthesis is still an open question, favored site is neutron star mergers

	core-collapse supernovae	neutron star mergers
rate [MW ⁻¹ Myr ⁻¹]	5000 – 12,000 Li+11, Horiuchi+11, Taylor+14	NS–NS: 25 – 400, NS–BH: 0.05 – 100 LIGO10, Dominik+15, deMink+15, LIGO17b
ejecta	$\text{few} \times 10^{-4} M_{\odot}$, $Y_e \gtrsim 0.4$ e.g. Wanajo13	$\sim 10^{-3} – 10^{-2} M_{\odot}$, $Y_e \sim 0.05 – 0.45$ see refs below *
challenges	not neutron-rich enough for full r-process (e.g. Fischer+10, Roberts+10, Martínez-Pinedo+12)	heavy elements present at early times, mixing (e.g. Qian00, Argast+04, Matteucci+14, but maybe no problem: e.g. Ishimaru+15, Cescutti+15)

* Surman+08, Wanajo+12, Fernández+13, Bauswein+13, Hotokezaka+13, Foucart+14, Perego+14, Just+15, Foucart+15, Sekiguchi+15, Kyutoku+15, Radice+16

Recent evidence for rare r-process

- Reticulum II: 1 in 10 highly r-process enhanced ultra-faint dwarf galaxy
- Recently discovered second UFD with r-process star: Tucana III
Hansen et al., 2017, ApJ 838, 1



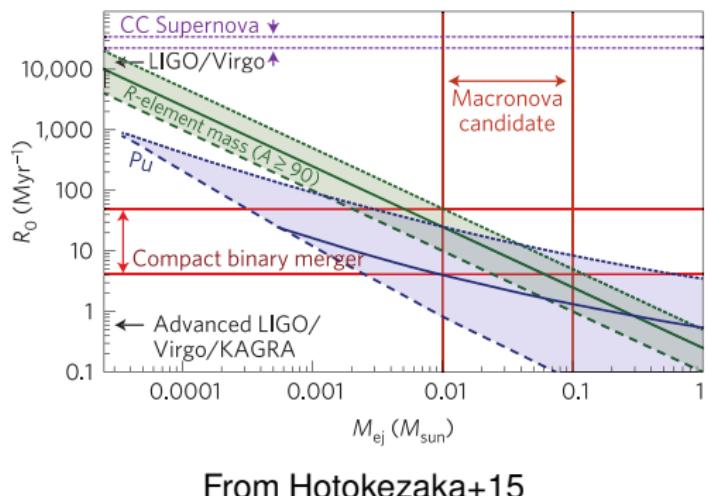
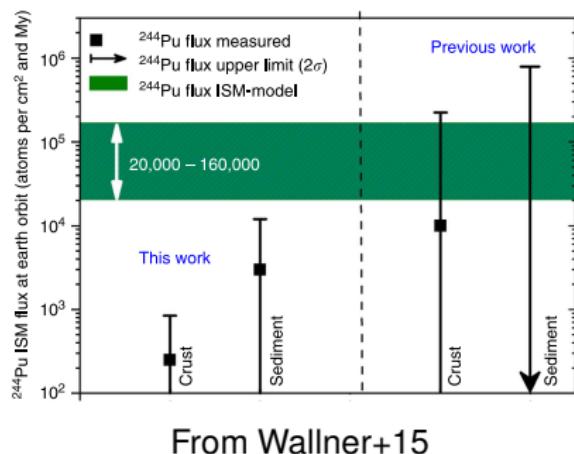
Ji et al., 2016, Nature 531, 610

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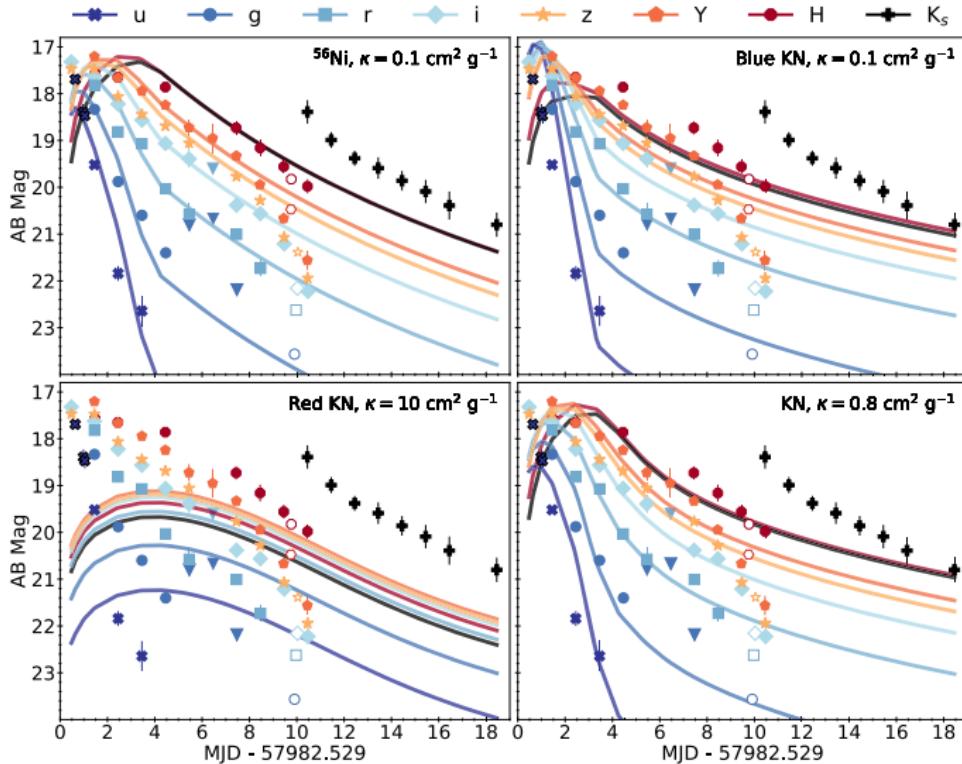
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Recent evidence for rare r-process

- ^{244}Pu is actinide (r-process only) with $\tau_{1/2} \sim 80 \text{ Myr}$ ($< \tau_{\text{mix}} \sim 300 \text{ Myr}$)
- Interstellar material is swept up and deposited in deep-sea crust
- Measure abundance of ^{244}Pu in 25 Myr old deep-sea crust \rightarrow ^{244}Pu abundance in ISM



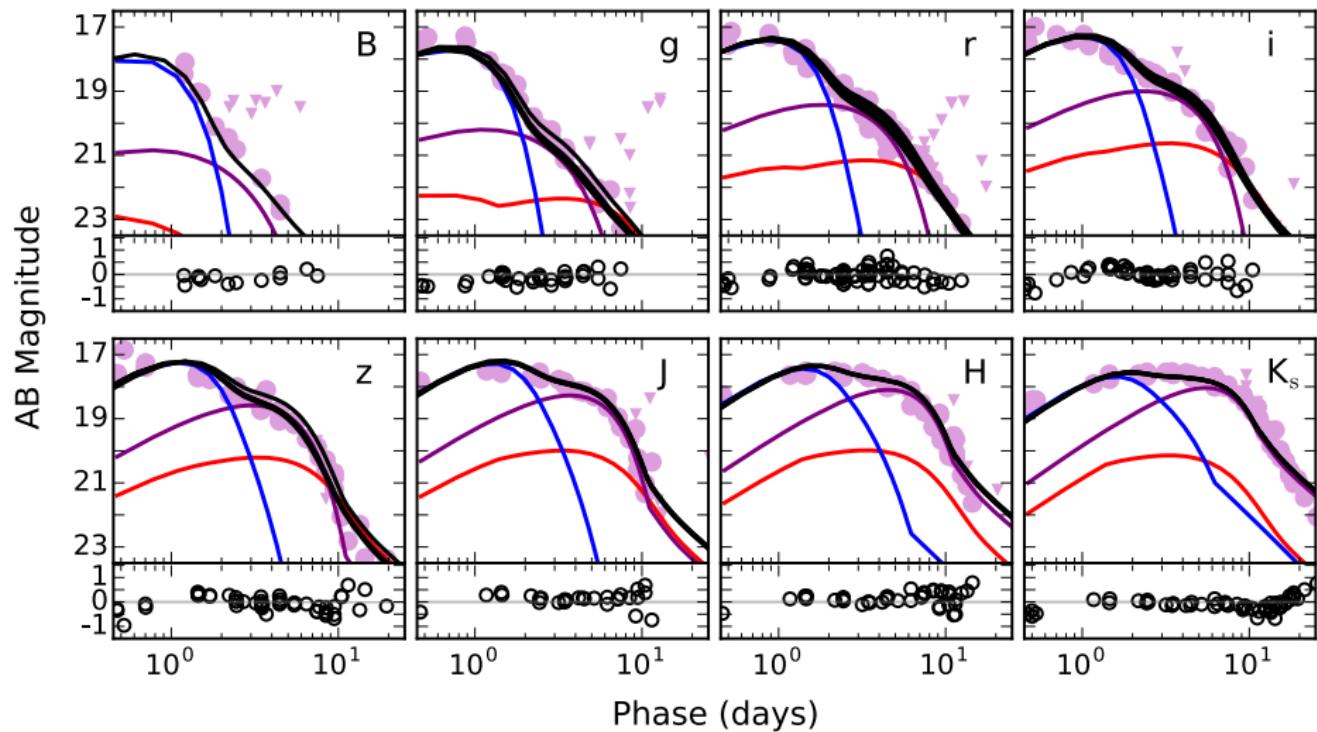
GW170817: One-component kilonova models fail



Cowperthwaite et al., 2017, ApJL 848, L17

UNCLASSIFIED

GW170817: Three-component model needed?

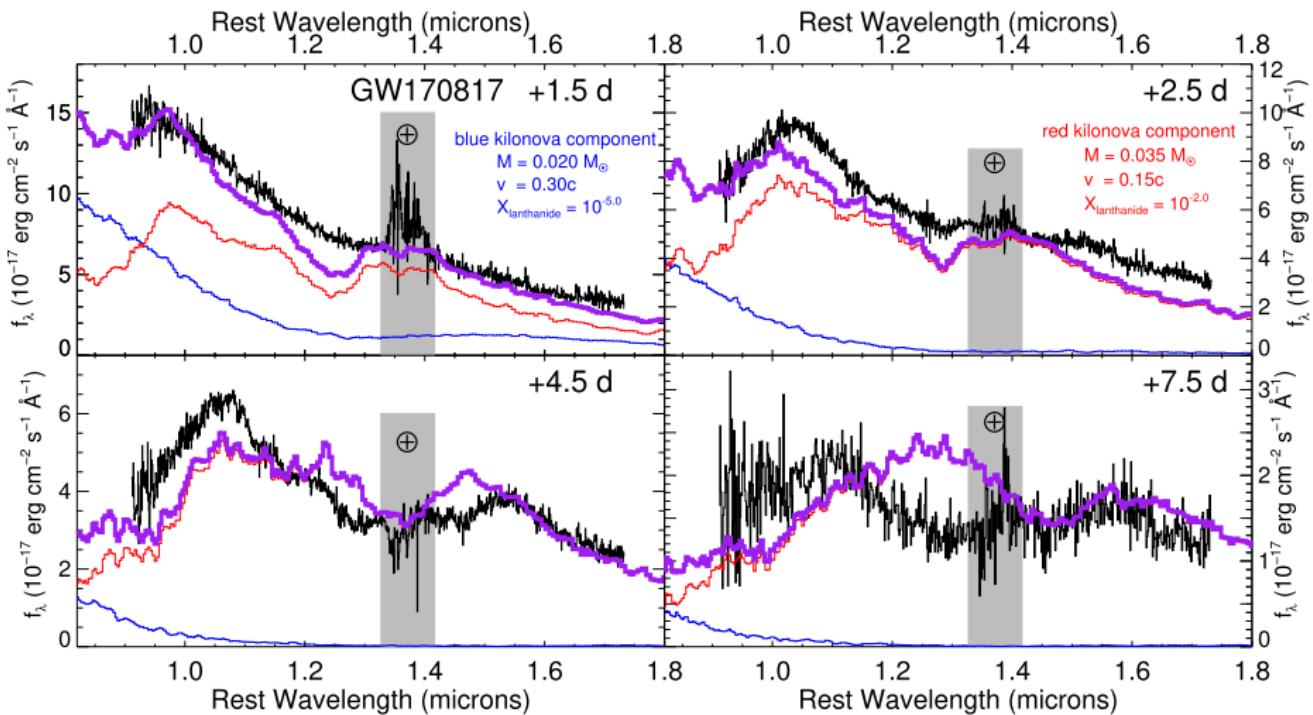


Villar et al., 2017, ApJL 851, L21

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GW170817: Infrared spectrum



Chornock et al., 2017, ApJL 848, L19

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